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Off-Main-Grid PV Systems: Appropriate Sizing Methodologies in Developing Countries

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“*Dedicato a tutti coloro che
con poco sanno sorridere*”

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Abstract

During the last years the problem of access to energy has become increasingly important in the eyes of the international community. The connection between access to energy and human development has become clearer but, despite the efforts spent in the last decades, the problem is far to be solved. This is true especially for the poorest countries, where the lack of access to energy is often one of the main obstacles to development.

Moreover, it is widely recognized that access to electricity can catalyse the solution of many problems, from providing lighting during nights, to improving education, health and information services.

Therefore, policy makers in developing countries, with the help of international organizations, are giving much importance to electrification. However, in rural areas the process will be slow due to high distance from the national grid, weak administration capacity, scattered villages, etc..

In this case, various options for supplying electricity need to be considered, but "Off-Main-Grid" decentralized technologies based on renewable sources already represent one of the most suitable solutions.

In this category, photovoltaic systems are the most successful technology in developing world especially for the resource availability, the extreme simplicity of application, the maturity of technology and the availability on the market.

Focusing on the "Off-Main-Grid" PV technologies, one of the most important aspects is to employ appropriate methodologies to size the components in order to best fit the system to the local targeted context.

Hence, in this work "Off-Main-Grid" Photovoltaic Systems are deeply investigated with particular attention to appropriate sizing methods for Stand-Alone Photovoltaic systems and PV Micro-Grid in developing countries. Stand-Alone Photovoltaic systems are discussed thanks to the author's experience on the field during the internship period of two months at Village Energy Uganda Ltd. During this period it was possible to analyse the context of Uganda and study the techno-economic approach of the company in order to develop an appropriate practical context-based sizing tool. On the other hand, the PV Micro-Grid matter has been addressed with an academic and scientific view through a critical assessment of the scientific literature with the aim to suggest a more appropriate sizing methodology for real-context based application in developing countries.

Keywords: access to energy; Stand-Alone photovoltaic systems; Micro-Grids; Numerical sizing models for Photovoltaic systems; Uganda; *HOMER*.

Sommario

Negli ultimi anni il problema dell'accesso all'energia è diventato sempre più importante agli occhi della comunità internazionale. Il nesso tra accesso all'energia e sviluppo umano è ormai chiaro, ma, nonostante gli sforzi profusi negli ultimi decenni, il problema è lungi dall'essere risolto. Questo è vero soprattutto per i Paesi più poveri, dove la mancanza di accesso all'energia è spesso uno dei principali ostacoli allo sviluppo.

E’ altresì ampiamente riconosciuto che l'accesso all'energia elettrica favorisce la soluzione di molti problemi, dalla possibilità di fornire illuminazione durante la notte all’opportunità di migliorare la qualità dell’istruzione, della sanità e dell’informazione.

Nei Paesi in via di sviluppo, con l'aiuto delle organizzazioni internazionali, si sta pertanto dando molta importanza all’elettrificazione, nella consapevolezza che tale processo sarà assai lento nelle zone rurali a causa della distanza dalla rete nazionale, delle deboli capacità amministrative e la diffusione dei villaggi.

In tali contesti devono quindi essere considerate varie opzioni per la fornitura di energia elettrica fra le quali le tecnologie decentrate "Off-Main-Grid", basate su fonti rinnovabili, rappresentano già una soluzione concreta.

All’interno di questa categoria, i sistemi fotovoltaici sono certamente la tecnologia più diffusa nei Paesi in via di sviluppo soprattutto per la disponibilità della risorsa, la semplicità applicativa, la maturità della tecnologia e la disponibilità di componenti sul mercato.

Focalizzando l’attenzione sui sistemi fotovoltaici "Off-Main-Grid", è di fondamentale importanza l’impiego di metodi adeguati per il dimensionamento dei componenti in modo tale da adattare al meglio il sistema al contesto locale in considerazione.

La tesi verterà quindi sull’analisi dei sistemi fotovoltaici "Off-Main-Grid" con specifica attenzione allo studio di metodi appropriati di dimensionamento per sistemi fotovoltaici Stand-Alone e PV Micro-Grid nei Paesi in via di sviluppo. In particolare i sistemi fotovoltaici Stand-Alone sono analizzati per mezzo dell'esperienza di tirocinio dell’autore presso Village Energy Uganda Ltd. Durante tale periodo è stato possibile osservare il contesto ugandese e studiare l'approccio tecnico-economico della società al fine di sviluppare un adeguato strumento di dimensionamento che fosse pratico per le loro esigenze. L'argomento riguardante le PV Micro-Grid è stato affrontato al contrario da un punto di vista accademico-scientifico, attraverso una valutazione critica della letteratura, con lo scopo di proporre una metodologia di dimensionamento più appropriata per applicazioni a contesti reali nei Paesi in via di sviluppo.

Parole chiave: Accesso all'energia; Fotovoltaico Stand-Alone; Micro-reti; Modelli numerici per il dimensionamento di sistemi fotovoltaici; Uganda; *HOMER*.

Estratto in lingua italiana

Introduzione

Il problema dell'accesso all'energia sta guadagnando sempre più posizioni nelle priorità dell'agenda globale. Il collegamento tra l'accesso all'energia e lo sviluppo umano sta diventando sempre più chiaro alle autorità politiche, alle agenzie internazionali, ONG, università, ecc. L'idea che sia responsabilità di un mondo giusto fare in modo che l'energia sia a disposizione di tutti in un modo pulito ed efficiente, costituisce ormai una base comune sulla quale basare ogni ragionamento futuro sul tema energetico.

Per quantificare la consistenza del problema vale la pena sottolineare che oggi 1,3 miliardi di persone non ha accesso all'elettricità e 2,7 miliardi si affida all’utilizzo di biomassa per scopi alimentare e per l'illuminazione. Questa situazione è localizzata principalmente nei Paesi in via di sviluppo, caratterizzati da economie a basso reddito e scarso consumo energetico pro-capite. In tale contesto l’accesso all'elettricità e l'utilizzo di servizi energetici moderni non sono disponibili per la maggior parte della popolazione, soprattutto nelle zone rurali.

E’ altresì ampiamente riconosciuto che l'accesso all'elettricità è la leva principale per lo sviluppo energetico. Ad oggi la realtà dei fatti dice che la distribuzione di energia elettrica nel mondo è ben distante dall'essere equa. Il tasso di elettrificazione nei Paesi in via di sviluppo si è attestato al 72% nel 2008 con punte negative di solo il 21% nei Paesi più arretrati localizzati principalmente nell’area sub-Sahariana. Proprio per segnare un punto di svolta in questa direzione i responsabili delle politiche energetiche di questi Paesi, con il supporto di organizzazioni internazionali, stanno dando molta importanza alla risoluzione del problema dell’elettrificazione, soprattutto nelle zone rurali. In tali aree devono essere considerate varie opzioni per la fornitura di energia elettrica come:

- Il collegamento alla rete elettrica principale;
- L’installazione di sistemi "Off-Main-Grid" decentrati rispetto alla rete nazionale, che possono essere ulteriormente suddivisi in:
    1. Home Based Systems;
    2. Community and Small & Medium Enterprise Based Systems;
    3. Micro-Grids: che possono basarsi su diverse tecnologie:
        - Tecnologie che sfruttano energie rinnovabili;
        - Generatori diesel;
        - Soluzioni ibride.

Tra le opzioni "Off-Main-Grid” i sistemi fotovoltaici "Off-Main-Grid” rappresentano una delle tecnologie di maggior successo nei Paesi in via di sviluppo, soprattutto per la disponibilità della risorsa, l'estrema semplicità di applicazione, la maturità della tecnologia e la disponibilità sul mercato. I sistemi fotovoltaici "Off-Main-Grid" possono essere classificati in due categorie:

1. Sistemi fotovoltaici Stand-Alone (SAPV): il cui scopo è di soddisfare le esigenze di un singolo cliente, sia esso una persona, una famiglia o un’attività commerciale. Tali sistemi possono essere ulteriormente suddivisi in base alle dimensioni in:
    - Pico Solar Systems;
    - Solar Home System (SHS);
    - Community Based Systems.

2. PV Micro-Grid: in grado di supportare le esigenze di un numero rilevante di famiglie e dei relativi servizi per la comunità.

La tesi verterà sull'analisi dei sistemi fotovoltaici "Off-Main-Grid" con particolare attenzione allo studio di metodi appropriati di dimensionamento per sistemi SAPV e PV Micro-Grid nei Paesi in via di sviluppo. I sistemi fotovoltaici SAPV sono analizzati per mezzo dell'esperienza di tirocinio dell'autore presso Village Energy Uganda Ltd. Durante tale periodo è stato possibile osservare il contesto ugandese e studiare l'approccio tecnico-economico della società al fine di sviluppare un adeguato strumento di dimensionamento che fosse pratico per le loro esigenze. L'argomento riguardante le PV Micro-Grid è stato affrontato al contrario da un punto di vista accademico-scientifico, attraverso una valutazione critica della letteratura, con lo scopo di proporre una metodologia di dimensionamento più appropriata per applicazioni a contesti reali nei Paesi in via di sviluppo.

Nel capitolo 1 è esposta un'analisi completa del Paese Uganda con particolare attenzione alla questione energetica al fine di fornire al lettore una panoramica del contesto in esame. Le attività svolte da Village Energy Uganda Ltd, uno delle imprese ugandesi attiva nell'installazione di sistemi fotovoltaici SAPV, sono esposte soffermandosi brevemente sui problemi esistenti e sulla soluzione sviluppata dall'autore durante il periodo di tirocinio.

Nel capitolo 2 sono analizzati dettagliatamente i sistemi fotovoltaici "Off-Main-Grid" attraverso uno studio delle metodologie di dimensionamento sviluppate nella letteratura scientifica e i dei software più comuni. Nella prima sezione è esposta la tecnologia che caratterizza questi sistemi attraverso un'analisi essenziale di ogni componente. Successivamente vengono presentati i principali layout al fine di individuare le differenze nelle applicazioni. Infine sono esaminate le metodologie di dimensionamento. In particolare due metodi di dimensionamento disponibili nella letteratura scientifica, i metodi intuitivo e numerico, ed il software commerciale *HOMER* sono descritti in dettaglio poiché verranno utilizzati nei capitoli successivi.

Nel capitolo 3 sono presentate le attività svolte dall'autore durante il periodo di stage di due mesi presso Village Energy Uganda Ltd. Dopo una breve introduzione che spiega le motivazioni del lavoro è presentato lo strumento di supporto decisionale sviluppato dall'autore, denominato *VE Sizing&Pricing*, che si propone come un'appropriata applicazione di un metodo intuitivo basata sull'analisi del contesto per dimensionare sistemi fotovoltaici SAPV. Infine è scelto un tipico caso studio e i risultati sono confrontati con quelli calcolati con *HOMER*.

Nel capitolo 4 sono approfondite le PV Micro-Grid per l'elettrificazione rurale e peri-urbana. Dopo una breve panoramica sulle ragioni che hanno motivato lo studio, è esposto il modello numerico implementato in MATLAB®. In seguito sono evidenziate le novità introdotte al fine di sviluppare un metodo di dimensionamento numerico che fosse appropriato per applicazioni basate su contesti reali in Paesi in via di sviluppo. Infine, è scelto un caso studio basato sul contesto ugandese ed è proposto il confronto dei risultati ottenuti con quelli calcolati con metodo intuitivo ed *HOMER*.

Capitolo 1

Uganda e Village Energy Ltd

Concentrando l'attenzione sulla questione energetica, l'approvvigionamento di energia primaria dell'Uganda (TPES) è predominato per il 90% dall'utilizzo di biomassa.

L’energia elettrica e i prodotti petroliferi contribuiscono per il rimanente 10%. Per quanto riguarda il valore pro-capite del TPES è quasi raddoppiato negli ultimi 30 anni, rimanendo comunque ben al di sotto della media mondiale e anche al di sotto della media sub-Sahariana. Considerando che la popolazione è quasi triplicata nello stesso periodo si può dedurre che oggi la richiesta di energia primaria del Paese è sei volte quella degli anni ottanta. Spostando l’attenzione sul consumo finale (TFC), come accade nella maggior parte dei Paesi meno sviluppati, la biomassa, essendo utilizzata per fini alimentari e di riscaldamento in ambito residenziale, pubblico ed industriale, rimane la più importante fonte di energia coprendo l'85% del TFC. A conferma di questo, l’intensità energetica si è attestata su valori medi elevati nel corso degli ultimi 20 anni, 2 volte superiori alla media mondiali. La spiegazione risiede certamente nella mancanza di efficienza di un'economia basata sull'uso di biomassa.

L’80% (29 milioni di persone) dell'Uganda non ha accesso all'elettricità. Il consumo di elettricità annuo pro capite è di 64,5 kWh, circa l'11% della media africana e il 2,5% della media mondiale. Circa il 72% dell’elettricità fornita dalla rete elettrica nazionale è consumata dal 12% della popolazione concentrata nelle aree metropolitane. Inoltre, i dati del Ministero dell'energia e dello sviluppo minerario dicono che il tasso di elettrificazione è solo il 12% su base nazionale (il restante 8% fa uso di generatori diesel o altri sistemi off-grid) e solo il 2% nelle zone rurali. Questo scenario comporta due problemi principali:

- Il 95% delle famiglie rurali non hanno accesso all'elettricità e utilizza tecnologie di illuminazione tradizionali, quali le lampade a cherosene che, emettendo fumi tossici, rappresentano un rischio sanitario.
- Il tentativo di trasformare l'Uganda da paese agricolo ad industriale è fortemente limitato dalla mancanza cronica di energia elettrica.

In questa situazione specifica e considerando che l’Uganda, trovandosi lungo l'equatore, può beneficiare di un elevato livello di irraggiamento solare (mediamente 5-6 kWh/m^2/giorno), i sistemi fotovoltaici "Off-Main-Grid" rappresentano una grande opportunità per l'elettrificazione rurale.

Oggigiorno i Solar Home System, sistemi SAPV che vanno dai 10 W ai 50 W di potenza nominale, rappresentano la domanda di mercato principale. Molte imprese sono attive nella creazione di prodotti standardizzati che siano in grado di intercettare le esigenze del cliente. La maggior parte di queste aziende non si trovano in Uganda, dove hanno invece solo sedi commerciali. Tali sistemi sono progettati in occidente, prodotti nell’est Asia e solo allora importati nel mercato ugandese per essere venduti a prezzi altamente concorrenziali. L'unica fetta di mercato non coperto da società straniere e che può essere colmata dall’attività di imprese locali è rappresentata dai sistemi personalizzati SAPV, su misura per le esigenze del cliente.

In tale contesto si inserisce la realtà di Village Energy Uganda Ltd, esposta attraverso l'esperienza dell'autore come studente tirocinante per un periodo di due mesi, dal 14 ottobre 2013 al 13 dicembre 2013. L'azienda è stata fondata nel 2008 dalla visione “better energy–better communities” di Abu Musuuza e Roey Rosenblith ed ha al suo attivo l’installazione di oltre 4500 sistemi solari in 15 distretti dell'Uganda. La sede centrale è in Kampala con un ufficio regionale a Soroti. L'azienda è composta da 8 dipendenti, 6 tecnici e 2 contabili guidati da 3 dirigenti. L’obiettivo della società è di aumentare l'accesso alle energie rinnovabili, a prezzi accessibili contribuendo quindi a stimolare le economie di comunità rurali e periurbane, offrendo la possibilità di migliorare lo stile di vita.

Come approfondito da Village Energy una famiglia rurale media vive di agricoltura di sussistenza. Tipicamente tale famiglia spende circa 30,000.00 scellini ugandesi al mese di cherosene per l'illuminazione e percorre lunghe distanze per la ricarica del telefono cellulare (pratica fondamentale poiché il sistema di credito ugandese si basa su movimenti di denaro attraverso l'utilizzo dei telefoni cellulari). Tali costi rappresentano circa il 15 % del loro reddito. Se queste famiglie investissero in un sistema solare da 10 W - 30 W, vedrebbero ammortizzati i costi di capitale entro un periodo di un anno e ridotti i costi energetici al 4 % del loro reddito per l'anno successivo. Sulla base di queste ed altre informazioni, Village Energy ha sviluppato prodotti standardizzati all'indirizzo di diverse categorie di consumo:

- Sistemi portatili: Freedom light and Musana 100;
- Famiglia rurale (medio-piccola): Musana range;
- Famiglia rurale (medio-grande): Entertainment systems
- Soluzioni per il Business: Phone charging system.

La Freedom Light è una luce a LED ricaricabile attraverso un pannello da 3 W, perfetta per la lettura e lo studio durante la notte. Il Musana 100 è un sistema plug and play costituito da un pannello da 10 W e da un box contenente tutto l'occorrente per il funzionamento. I sistemi Musana ed Entertainment (esposti in tabella) sono stati progettati per soddisfare le esigenze delle famiglie rurali fornendo diverse soluzioni che intercettino il budget di ogni cliente. Infine il Phone charging system ha la capacità di caricare fino a 30 telefoni al giorno permettendo guadagni discreti al suo possessore.

Feature	**Musana 500**	**Musana 1000**	**Ent. Syst. 1**	**Ent. Syst. 2**	**Ent. Syst. 3**
Solar Panel	20 W	30 W	60 W	70 W	80 W
Lead-acid Battery	18 Ah	24 Ah	50 Ah	50 Ah	70 Ah
Charge Controller	5 A	5 A	20 A	20 A	30 A
LED lights	4	8	4	8	8
Phone charger	yes	yes	yes	yes	yes
Television	no	no	14”	14”	20”
Price [UGX]	**654.000**	**947.000**	**2.014.000**	**2.243.000**	**2.865.000**

Village Energy si occupa anche dell'installazione di tutti quei sistemi che la necessitano offrendo anche garanzie e servizi di manutenzione e sostituzione dei componenti.

Lo scopo principale dello stage è stato di contribuire a migliorare la competitività e l'efficienza di Village Energy. Come primo passo si sono quindi messi in evidenza i principali problemi che mettono a dura prova la sopravvivenza della società:

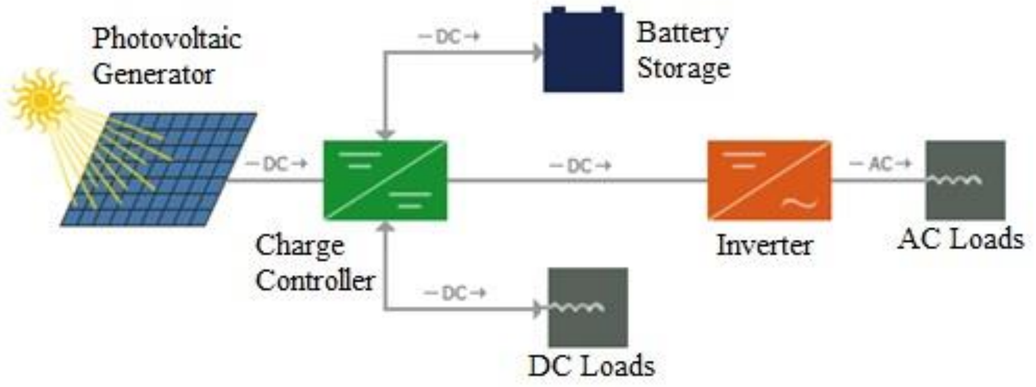
1. La forte concorrenza presente sul mercato ugandese;
2. La scarsa disponibilità economica del cliente;
3. Le difficoltà finanziarie della società;
4. La lentezza operativa.

Il secondo passo è stato focalizzare l'attenzione e cercare di trovare una soluzione ad uno di questi problemi. In accordo con la dirigenza si è quindi scelto Il quarto problema essendo l'unico che richiedesse una soluzione tecnica. Il *VE Sizing&Pricing* (il cui funzionamento è ampiamente spiegato nel cap. 3) è stato creato e pensato come uno strumento di supporto decisionale per dare una risposta a tale problema. Composto da semplici fogli in Microsoft Excel permette di dimensionare sistemi SAPV dando la possibilità a qualsiasi impiegato di Village Energy di fornire preventivi in pochi minuti al cliente.

Capitolo 2

Sistemi fotovoltaici "Off-Main-Grid": metodologie di dimensionamento e il software HOMER.

Il layout tipico di un sistema fotovoltaico "Off-Main-Grid" è rappresentato nella figura sottostante. Tali sistemi sono progettati per funzionare indipendente dalla rete elettrica e devono essere in grado di alimentare anche i carichi elettrici a corrente continua od alternata che possono verificarsi durante la notte. E' necessario quindi aggiungere un sistema di accumulo e generalmente è utilizzata la soluzione a batteria per questo scopo. Nel caso in cui il sistema debba alimentare carichi in corrente alternata è necessario anche un inverter. Infine deve essere aggiunto un regolatore di carica al sistema con lo scopo di mantenere la batteria al più alto stato di carica possibile, proteggendola da sovraccarichi dal generatore fotovoltaico e da eccessivi scaricamenti.



Nella letteratura scientifica sono presenti tre metodologie di dimensionamento per sistemi "Off-Main-Grid". Ognuna di esse richiede dati sul carico e sulla risorsa che possono variare in termini di dettaglio temporale e precisione nella misurazione. Inoltre, alla base di ogni metodo dimensionamento ci sono ipotesi circa la particolare modellizzazione dei componenti del sistema, il grado di complicazione dei quali varia secondo la precisione dei risultati che si vogliono ottenere e lo scopo dell'analisi. In ogni caso, tali metodologie di dimensionamento forniscono sempre risultati quantitativi in termini di dimensione dei pannelli e batterie e, spesso, di costo totale attualizzato netto del sistema. Le procedure di dimensionamento in considerazione sono:

1. I metodi intuitivi: i quali forniscono un calcolo semplificato della dimensione del sistema effettuata senza stabilire alcun rapporto tra i diversi sottosistemi e senza tenere in conto della natura casuale della radiazione solare e dei carichi. Sono per lo più scelti per la loro semplicità di calcolo che li rende più comprensibili e replicabili dal progettista non esperto. Il punto negativo di tale approccio è l'approssimazione dei risultati che può facilmente condurre and un sovradimensionamento o sottodimensionamento dell'impianto.
2. I metodi numerici: in cui sistemi diversi, (cioè diverse combinazioni di pannelli e batterie), sono simulati su base annua e un criterio comune consente di scegliere la migliore combinazione che risponde al carico. Per ogni intervallo temporale considerato, di solito orario, il bilancio energetico del sistema e la variazione dello stato di carica della batteria è calcolato. Generalmente tali metodi sono preferiti

quando sono necessari risultati più accurati al fine di ottimizzare l'energia e il costo economico del sistema. I metodi numerici hanno anche il vantaggio di consentire l’analisi di ulteriori aspetti del dimensionamento come l’impatto che hanno diversi modelli descrittivi dei componenti sui risultati. Gli svantaggi sono invece il tempo di calcolo richiesto e la necessità di lunghe ed accurate sequenze di dati di input.

3. I metodi analitici: nei quali si necessita delle relazioni funzionali tra le variabili di interesse per risolvere il problema di dimensionamento, sono quindi normalmente sviluppati come un problema di ottimizzazione matematica con una funzione obiettivo sottoposta a una o più condizioni. Uno dei principali difetti di questi metodi è che o non sono sufficientemente accurati o richiedono la determinazione di coefficienti specifici per le relazioni funzionali. Il loro maggiore vantaggio è che la simulazione dei diversi sottosistemi è semplice e relativamente veloce.

Come risultato di quanto appena esposto, sul mercato sono già a disposizione software che implementano queste diverse metodologie e che forniscono automaticamente i risultati richiesti sulla base di input dall'utente. Essi possono essere riassunti in due categorie principali:

1. Programmi che utilizzano principalmente la metodologia intuitiva per fornire informazioni sulle prestazioni di un impianto fotovoltaico. I più noti sono:
   - PVGIS sviluppato dalla Commissione europea;
   - RETScreen sviluppato da CANMET;
   - NSOL sviluppato da Fear The Skunk.
2. Software di simulazione che si basano sostanzialmente su metodi numerici o analitici. I più noti sono:
   - HOMER sviluppato da NREL;
   - TRNSYS sviluppato da Solar Energy Lab;
   - PV * SOL Expert di Valentin Software Energy.

I metodi intuitivi e numerici sono selezionati per ulteriori sviluppi e dettagliati nelle sezioni del capitolo in quanto alla base delle applicazioni successive. Per ciascun metodo è esposto in primo luogo il procedimento generale con l'aiuto di diagrammi di flusso schematici e, successivamente, sono descritte tutte le principali modifiche alla struttura di base riscontrabili in letteratura. Inoltre è presentata, una breve ma esauriente panoramica del software *HOMER* poiché è stato riscontrato essere lo strumento più utilizzato per l'analisi di sistemi "Off-Main-grid" e soprattutto perché è utilizzato per confrontare i risultati ottenuti nell'applicazione dei metodi intuitivi e numerici presenti nei successivi capitoli.

Capitolo 3

Dimensionamento di sistemi SAPV: un appropriato metodo intuitivo basato sul contesto Ugandese.

Come spiegato nel Capitolo 1 diversi problemi minano la sopravvivenza di Village Energy Uganda Ltd. Tuttavia una marcata lentezza operativa è stata individuata come un chiaro vincolo allo sviluppo delle attività di business. Si necessita infatti di lunghi tempi per chiudere un ordine, a volte passano alcuni mesi dal primo contatto con il cliente al preventivo finale. Le cause sono principalmente due:

1. Una forte dipendenza dal capo-tecnico che è l'unico in grado di decidere, grazie ad anni di pratica, quale sia la dimensione corretta del sistema da installare per soddisfare il carico richiesto dal cliente.
2. La mancanza di una banca dati contenente specifiche e prezzi standard dei vari componenti.

In accordo con la dirigenza, il *VE Sizing&Pricing* è stato pensato come uno strumento di supporto alle decisioni. Composto da semplici fogli di calcolo Microsoft Excel, è stato costruito dall'autore per rendere chiunque in Village Energy in grado di dimensionare un sistema SAPV e fornire un preventivo corretto al cliente. Per giungere all'obiettivo, l'utente deve seguire quattro fasi che corrispondono a quattro fogli di calcolo Microsoft Excel:

1. La prima fase prevede l'interazione tra il cliente e l'impiegato di Village Energy. Le informazione del cliente sono ordinate in un primo foglio di calcolo Microsoft Excel, denominato *Device sheet*. Per ogni apparecchio che il cliente vuole alimentare, informazioni riguardanti il numero, il consumo in potenza e le ore giornaliere e notturne di utilizzo sono richieste e utilizzate per modificare una lista già pre-impostata di dispositivi comuni. Come risultati di questa prima fase, l'utente può visualizzare il carico totale, giornaliero e notturno oltre che la potenza massima richiesta da tutti i dispositivi.
2. La seconda fase prevede il dimensionamento del sistema SAPV in un secondo foglio di calcolo denominato *Sizing Sheet.* In questo passaggio l'utente deve solo leggere i risultati del dimensionamento in termini di potenza dei pannelli fotovoltaici, capacità delle batterie e dimensioni del controller ed inverter da installare in modo da soddisfare le esigenze del cliente. Si noti che risultati intermedi emergono dalle equazioni del metodo intuitivo implementato dietro le celle del foglio di calcolo. Successivamente tali risultati sono automaticamente confrontati con i database dei componenti (costruiti sulla base di un'indagine di mercato svolta dall'autore e riguardante i principali fornitori di Village Energy) effettivamente acquistabili sul mercato per ottenere il dimensionamento finale.
3. La terza fase è rappresentata dalla compilazione del foglio di calcolo denominato *Pricing sheet*. L'utente deve scegliere la qualità dei componenti, cioè per esempio il tipo di pannelli (monocristallini o policristallini), il tipo di regolatore di carica ed inverter ed il numero o la lunghezza di tutti gli altri componenti come per esempio cavi, interruttori, sostegni per i LED etc., necessari per completare l'installazione presso il cliente. Anche in questo caso la scelta è guidata perché, se l'utente non è sicuro, può fare affidamento a risultati automatici derivanti da alcune equazioni empiriche basate su installazioni precedenti. Infine vi è la possibilità di variare anche il margine di profitto ed il margine a copertura dei costi operativi nel caso in cui cambi la strategia aziendale oltre che le eventuali percentuali di commissioni nel caso il cliente sia stato procurato da agenti esterni alla società. In tale foglio di calcolo, l'utente può scegliere i componenti necessari avvalendosi di comodi menù a tendina, Il sistema quindi funziona automaticamente prendendo il prezzo corretto dal database e fornendo come risultati finali il costo totale dei componenti, utile alla società, e il prezzo totale del sistema da fornire al cliente.
4. La quarta ed ultima fase prevede la compilazione dell'ultimo foglio di calcolo denominato *Quotation sheet*. L'utente deve inserire il nome del cliente, controllare se si siano verificati errori nella copia automatica dal foglio precedente e infine stampare tale foglio di calcolo come preventivo per il cliente. Egli può così visualizzare tutte le informazioni di cui necessita su un singolo foglio di carta che

presenta il logo dell'azienda nella parte superiore, tra le quali un chiaro elenco di tutti i componenti che la società installerà, il costo della manodopera ed il prezzo finale del sistema SAPV. Nell'ultima parte sono specificate la validità del preventivo, la tempistica per l'installazione, le garanzie sui componenti ed eventuali costi non inclusi.

Nel capitolo è esposto come ciascuna delle quattro fasi che caratterizzano il *VE Sizing&Pricing* è stata implementata dall'autore. Le equazioni di riferimento e le tabelle con i dati principali sono esposte a supporto della lettura.

Nelle sezioni seguenti è presentato un tipico caso studio di un sistema personalizzato SAPV. Il caso studio è localizzato nella zona rurale che circonda la piccola cittadina di Soroti in Uganda dove Village Energy Ltd ha una sede distaccata. Sulla base degli ordini più ricorrenti si è immaginato un cliente tipico che necessiti di un sistema SAPV con lo scopo di alimentare gli apparecchi già presenti nella casa dove vive con la famiglia. Seguendo il procedimento in 4 fasi, sulla base del calcolo del carico totale richiesto, pari a circa 3.7 kWh/giorno. si è dimensionato il sistema SAPV ottenendo i risultati esposti nella tabella di cui sotto. Infine il calcolo del preventivo (esposto in Appendice) ha condotto ad un prezzo finale, al netto dei margini operativi e di profitto, di circa 7 milioni di scellini ugandesi.

Tale caso studio è stato utilizzato anche per studiare la fattibilità economica rispetto al classico utilizzo di piccoli generatore diesel. Si è potuto concludere che tali sistemi SAPV sono competitivi su una prospettiva di 10 anni pur in assenza di incentivi o aiuto all'investimento da parte delle istituzioni competenti.

INVERTER SIZING		
Inverter power to be installed	**1000**	**W**
Voltage of the DC bus	24	V
PV ARRAY SIZING		
Minimum nominal power required	688.89	W
Rated power of each panel installed	240	W
Number of installed panels of the same rated power	4	
PV array power to be installed	**960**	**W**
BATTERY BANK SIZING		
Energy of storage	2.34	kWh
Minimum capacity of batteries to be allocated	162.78	Ah
Rated Capacity of each battery installed	200	Ah
Number of installed batteries of the same rated capacity	2	
Battery Bank capacity to be installed	**200**	**Ah**
CHARGE CONTROLLER SIZING		
Maximum current	40	A
Charge controller to be installed	**40**	**A**

Nell'ultima sezione del capitolo sono calcolati anche i risultati che si otterrebbero con *HOMER* sulla base dello stesso caso studio. Riconoscendo che tale software lavora come un metodo numerico, le impostazioni di default sono state modificate con lo scopo di comprendere l'adattabilità e la praticabilità del software in un contesto specifico come quello in cui opera Village Energy. Il confronto finale tra i risultati, sulla base dell'esperienza maturata dall'autore dopo due mesi trascorsi nella realtà operativa dell'azienda, ha permesso di concludere che *HOMER* è sicuramente uno strumento più sofisticato rispetto a *VE Sizing&Pricing*, tuttavia la specificità degli input necessari e le numerose limitazioni lo rendono inadeguato per un contesto reale come quello in considerazione. *VE Sizing&Pricing* risulta quindi essere più appropriato per rispondere alle necessità di Village Energy Uganda Ltd. E' infatti:

- Semplice ma preciso: guida automaticamente l'utente verso la compilazione del preventivo. Fornisce inoltre risultati dimensionali che sono stati validati in termini di precisione con quelli ottenuti con *HOMER*.
- Veloce: essendo progettato per funzionare automaticamente approfittando di informazioni già pre-impostate, permette all'utente di generare un preventivo in pochi minuti;
- Flessibile: le numerose informazioni presenti in ogni foglio di calcolo Microsoft Excel possono essere modificate rendendo lo strumento adattabile a qualsiasi particolare richiesta del cliente;
- Market-based: presentando un dettagliato database che raccoglie le informazioni dei componenti presenti sul mercato, permette di fornire risultati adattati al contesto locale.
- Modificabile in futuro: il database, l'approccio di dimensionamento e le ipotesi economiche possono essere modificate a seguito di cambiamenti nella strategia aziendale.

Come sviluppo futuro dovrebbe essere presa in considerazione la raccolta di ulteriori informazioni circa gli attuali costi energetici del cliente per fornire automaticamente un’analisi comparativa che ponga l’accento sull’analisi di rientro dall’investimento, al fine di fornire maggiori dettagli e permettere al cliente di decidere non solo sulla base del costo di investimento.

Capitolo 4

Dimensionamento di una PV Micro-Grid: un appropriato metodo numerico per i Paesi in via di sviluppo.

E' possibile sintetizzare le motivazioni che hanno condotto ad approfondire lo studio di una PV Micro-Grid in tre aspetti principali:

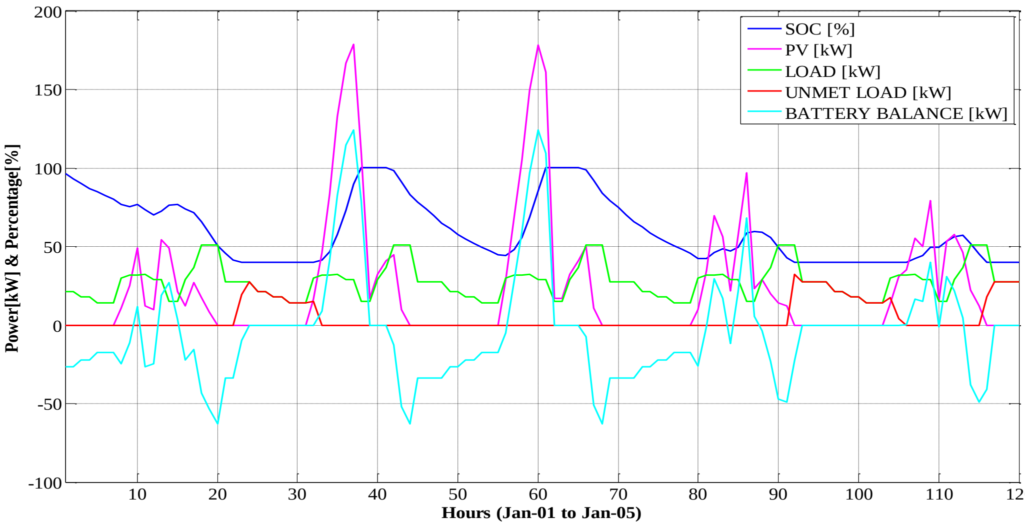
1. L'interesse nell’indagare i vantaggi e gli svantaggi dei metodi numerici per il dimensionamento di sistemi fotovoltaici "Off-Main-grid". Particolare attenzione è stata posta nel verificare la possibilità di rendere tali metodi appropriati al contesto rurale in Paesi in via di sviluppo.
2. Le PV Micro-Grids rappresentano una valida alternativa per l'elettrificazione rurale e peri-urbana ai sistemi SAPV. I vantaggi sono in termini di affidabilità e costo totale potendo usufruire di economie di scala. Inoltre, mentre i sistemi SAPV, essendo di piccole dimensioni, difficilmente possono essere presi in considerazione nella pianificazione energetica dei Paesi in via di sviluppo, ma possono al massimo beneficiare di incentivazione da parte delle istituzioni nazionali, le PV Micro-Grids, avendo l'obiettivo di raggiungere un numero significativo di utenti, possono invece godere di maggiore attenzione da parte delle autorità centrali che possono valutare la possibilità di installare tali sistemi per compensare la mancanza di diffusione della rete nazionale.
3. Il forte interesse nella comunità scientifica sulla materia delle Micro-Grids soprattutto in termini di approccio di dimensionamento, pianificazione, simulazione

e controllo. Nel quadro dei sistemi fotovoltaici "Off-Main-Grid", le Micro-Grid, basate sulla sola fonte fotovoltaica con accumulo da batteria, sono state scelte come oggetto di tale capitolo contestualizzando tale soluzione nei Paesi in via di sviluppo, con particolare riferimento al caso dell'Uganda.

In questo contesto, nella prima fase si è ricostruita l'operatività fisica di una PV Micro-Grid attraverso lo sviluppo di un codice in MATLAB® basato su metodo numerico. Avendo chiaro l'obiettivo principale della trattazione, cioè quello di focalizzare l'attenzione sull'adeguatezza del metodo di dimensionamento, il modello fisico descrittivo del sistema è stato sviluppato partendo da una descrizione ideale e successivamente introducendo un maggior dettaglio che cercasse di tener conto del comportamento reale del sistema seguendo quanto di più consolidato si attesta nella letteratura scientifica. La modellizzazione del carico, della risorsa e di tutti i componenti del sistema sono quindi esposti in un'apposita sezione del capitolo.

In una seconda fase si è simulato il comportamento (di cui si ha riscontro in figura) di diverse combinazioni di componenti al fine di avere risultati tra cui scegliere l'impianto ottimo. Ovviamente alcune impostazioni, come il passo temporale ed il range di simulazione, sono state fissate comuni a tutte le simulazioni, mentre i parametri di performance monitorati su base annua sono stati i seguenti:

- Loss of Load Probability (LLP): la percentuale del carico totale richiesto dall'utente che resta non soddisfatta;
- Loss of Photovoltaic energy Probability (LPVP): la percentuale di energia producibile da fotovoltaico che non è sfruttata dal sistema;
- Net Present Cost (NPC): il costo totale attualizzato netto del sistema durante la sua vita utile.



Nella terza e fondamentale fase rientra la ricerca dell'appropriatezza del modello proposto che ha riguardato il criterio che il metodo numerico usa per scegliere la migliore combinazione di componenti che risponde al carico. Si è quindi definita una funzione obiettivo che fosse appropriata, se applicata al contesto rurale in Paesi in via di sviluppo, per determinare l'impianto ottimale.

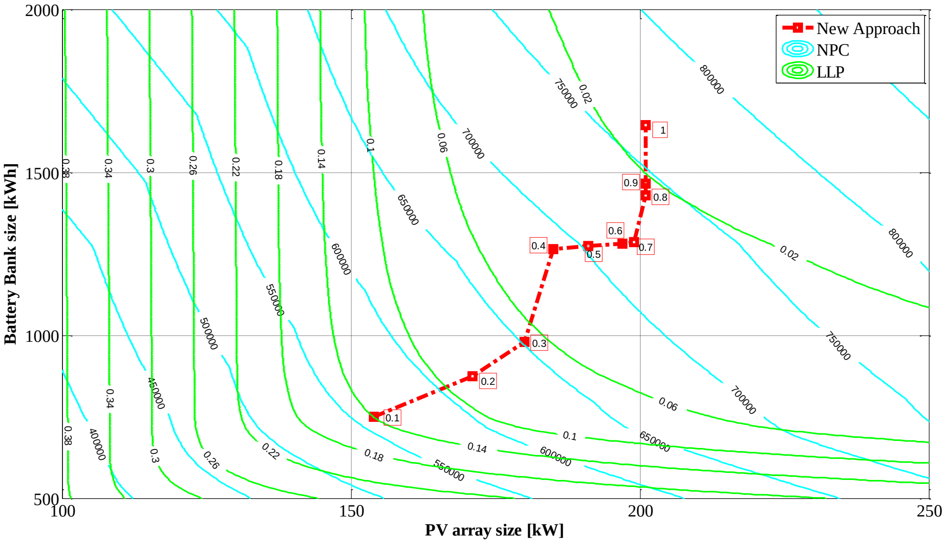
Da questo punto di vista, l'approccio classico utilizzato in letteratura consiste nel fissare un LLP specifico e determinare quale tra gli impianti che lo soddisfano presenta il minimo NPC. Tuttavia si sono riscontrate tre limitazioni:

1. L'impossibilità di definire l'LLP: non è infatti realistico pensare che il progettista o il cliente sappiano quale sia il carico massimo che può rimanere non soddisfatto.
2. Il costo attualizzato netto non tiene conto di tutti i costi energetici che il cliente dovrà affrontare durante la vita utile dell'impianto. E' infatti possibile immaginare che se la PV Micro-Grid lascia scoperti alcuni carichi nel corso degli anni come espresso dalla percentuale dell'LLP, questo significa che l'utente tornerà al sistema precedente, con i costi connessi, per soddisfare tale carico.
3. La fase di ottimizzazione è in due fasi: il progettista deve trovare tutti i sistemi che rispondano il carico rispettando il valore LLP fissato e successivamente ordinarli in merito all'NPC per determinare il migliore.

Si propone quindi un nuovo approccio basato sull'impostazione di un valore economico per il carico non soddisfatto (LL_{value}) dalla PV Micro -Grid. In questa prospettiva, l'LLP cumulato nell'anno simulato di funzionamento non è più un parametro da fissare ma è usato per calcolare un nuovo flusso di cassa negativo utile per ottenere un nuovo NPC. Tuttavia, riconoscendo la necessità di aggiungere un ulteriore fattore che tenga conto della soddisfazione del carico non solo da un punto di vista strettamente economico, unito all'obiettivo di rendere il modello MATLAB® in grado di determinare il miglior sistema in un solo passaggio, la scelta della funzione obiettivo si è indirizzata verso il costo dell'energia (LCOE) così come da definizione IEA opportunamente modificata per il contesto in esame come segue:

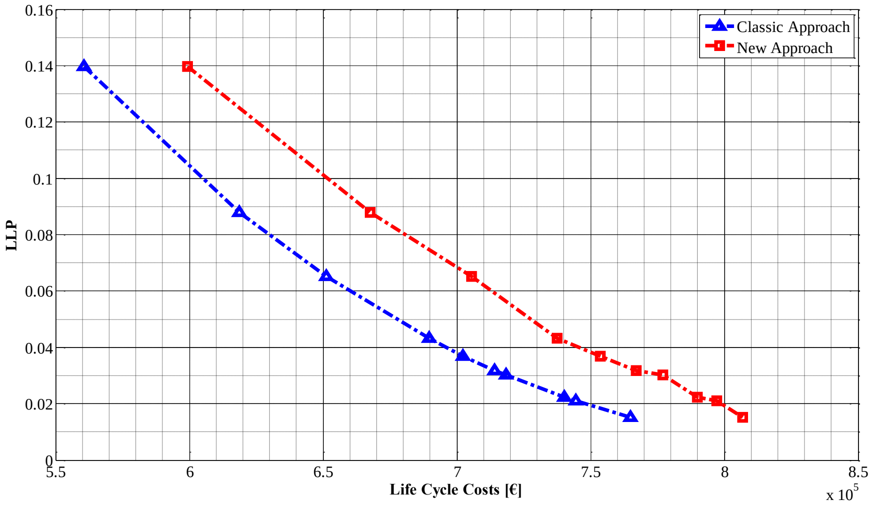
$$f_{obj} = LCOE_{mod} = \frac{C_{Invest} + \sum_{i=1}^{\mathrm{LC}} \frac{CF_i + \left(\sum_{t=1}^{8760} \mathrm{LL}(t)\right) \cdot LL_{value}}{(1+r)^i}}{\sum_{i=1}^{LC} \frac{E_L(1-LLP)}{(1+r)^i}}$$

Tale funzione presenta un minimo ed è appropriata per il contesto perché si riconosce quanto più immediato sia per il progettista dare una valorizzazione del carico non soddisfatto anziché dover impostare la percentuale dell'LLP (che, nel nuovo approccio, è un parametro risultante dalla fase di ottimizzazione). Tale valore può essere calcolato con diversi livelli di precisione sulla base di una stima dei costi energetici precedenti all'installazione della PV Micro-Grid. Nella figura sottostante è evidenziata la curva di dimensionamento basata sul nuovo approccio per valorizzazione del carico non soddisfatto variabile.



Nel proseguo del capitolo, sotto forma di una mappa integrativa è fornita un'indicazione della sensibilità del punto di ottimo. Tale mappa mostra tutti i sistemi che hanno un valore della funzione obiettivo che non si discosti di più dell'1 % dal valore minimo ed è fondamentale perché permette al progettista di riconnettersi con la realtà dei componenti disponibili sul mercato locale e mostra chiaramente le regioni corrispondenti a diverse valorizzazioni economiche del carico non soddisfatto, permettendo di assorbire eventuali errori sulla stima di tale parametro.

Successivamente si propone un confronto fra i due approcci per delinearne le congruenze e le divergenze. Tale raffronto si manifesta nella figura di cui sotto in cui si esplica che il nuovo approccio considera la totalità dei costi energetici a carico dell’utente.



Infine, con lo scopo di verificare la consistenza dei risultati ottenibili con il modello sviluppato in MATLAB® con quelli che si otterrebbero con l'applicazione delle due metodologie indagate in questa tesi, si è analizzato un caso studio localizzato nell’area rurale di Soroti. Sulla base dei dati raccolti dall’autore sul campo si sono potute stimare una curva di carico realistica e una valorizzazione sensata del carico non soddisfatto. Sono quindi esposti i risultati di dimensionamento ottenuti con il modello MATLAB®, con metodo intuitivo generale e con *HOMER* il quale applica l’approccio classico di dimensionamento del metodo numerico.

Come futuri sviluppi dovrebbero essere presi in considerazione ulteriori studi sulla stima della curva di carico con l'obiettivo di ottenere un passo temporale più dettagliato. Sarebbe pertanto consigliabile ridurre coerentemente il passo temporale di simulazione, sviluppando modelli descrittivi dei componenti che siano in grado di sfruttare tale dettaglio con particolare attenzione alla stabilità e all'affidabilità del sistema. In questo senso sarebbe di primaria importanza lo sviluppo di un modello di batteria più accurato soprattutto per quanto riguarda la determinazione del SOC in relazione alle condizioni di lavoro. Infine, riconoscendo che la valutazione della valorizzazione del carico non soddisfatto è stata condotta senza un’analisi dei possibili approcci disponibili, sarebbe anche necessario approfondire la letteratura specifica e prendere in considerazione la possibilità di sviluppare una metodologia più dettagliata che sia adattabile alla particolare applicazione di questo lavoro.

Conclusioni

In questa tesi sono stati studiati ed approfonditi i sistemi "Off-Main-Grid" con particolare attenzione allo sviluppo di metodi appropriati di dimensionamento per sistemi fotovoltaici stand-alone (SAPV) e PV Micro-Grids nei Paesi in via di sviluppo.

Il problema dell'accesso all'energia con particolare riferimento all’elettrificazione rurale rappresenta il contesto generale di inserimento della tesi. Il tirocinio presso Village Energy Uganda Ltd ha permesso all’autore di comprendere appieno sul campo tali problematiche, fornendo quindi il contesto specifico nel quale localizzare i casi studio presentati nella tesi, ma soprattutto di raccogliere le informazioni per poter validare l’appropriatezza delle metodologie proposte. Lo studio della letteratura in materia ha fornito le solide basi su cui poggiare lo sviluppo sia del *VE Sizing&Pricing*, uno strumento di supporto decisionale composto da fogli di calcolo Microsoft Excel per il dimensionamento di sistemi SAPV, sia del modello numerico implementato in MATLAB®, un simulatore che utilizza un nuovo approccio di metodo per dimensionare PV Micro-Grids.

In particolare il *VE Sizing&Pricing* si è concluso essere uno strumento più appropriato per le necessità di Village Energy Uganda Ltd se confrontato con HOMER, in quanto risponde a quelle caratteristiche di semplicità, velocità e flessibilità richieste dalla compagnia. Inoltre la presenza di database integrati nello strumento che raccolgono le informazioni dei componenti presenti sul mercato, permette di fornire risultati adattati al contesto locale.

Per quanto riguarda il modello numerico MATLAB® per il dimensionamento di PV Micro-Grids si è concluso essere più appropriato per applicazioni in aree rurali in Paesi in via di sviluppo grazie al nuovo approccio di metodo implementato. Infatti si è dimostrato come esso dia risposta alle principali limitazioni dell’approccio classico presente in letteratura (implementato anche in *HOMER*) attraverso:

- Il calcolo della valorizzazione del carico non soddisfatto ed il suo utilizzo come punto di partenza del processo di ottimizzazione piuttosto che l’LLP;
- Il conseguente calcolo di un NPC modificato che tenga in conto dei reali costi energetici che l’utente sosterrà durante il ciclo di vita dell’impianto;
- L’utilizzo dell’LCOE come funzione obiettivo in grado di fornire direttamente l’impianto ottimo senza bisogno di ulteriori passaggi.
- Lo sviluppo di una mappa di dimensionamento che fornisca informazioni di sensitività del punto di ottimo in relazione a variazioni della funzione obiettivo. Infatti, riconoscendo come i risultati del modello siano da intendersi preliminari, lo scopo è di permettere al progettista che studia l’installazione di tale sistema di ricollegarsi con la realtà dei componenti effettivamente reperibili in loco.

Introduction

In the last years, the issue of access to energy has climbed positions in the priorities of the global agenda. The connection between access to energy and human development is becoming clearer to policy makers, international agencies, NGOs, academia, etc.. It is rising up the idea that it is responsibility of a just world making sure that energy is available to all in a clean and efficient way.

In this perspective, international organizations have formulated indicators to explain development and energy systems progress with an inclusive approach that goes beyond the single economic factor or energy consumption factor. Main examples are the Human Development Index (HDI) and the Energy Development Index (EDI). HDI was first presented by UNDP in the 1990 [1]; its aim is ‘‘*to shift the focus of development economics from national income accounting to people centred policies*”, considering aspects such as life expectancy, access to education and standards of living. EDI has recently been developed by IEA [2] “*in order to better understand the role that energy plays in human development”*, it is a combination of four indicators, mainly related to electricity and modern fuels, which take in account different aspects of energy poverty. The correlation between EDIs and HDIs indexes is evident in Fig 0.1 where to an increase of EDI corresponds an increase of HDI. This highlights that when access to energy improves in terms of quality and quantity (increased shares of population with access to modern energy forms and more consumption of modern energy within the different sectors, which are the dimensions of EDI), also human development improves (increase of life expectancy, education level and income, which are the dimensions of HDI).

To identify the extent of the problem it is worthwhile to mention that today 1.3 billion of people do not have access to electricity and 2.7 billion rely on biomass for cooking and lighting [3]. This situation is localized mainly in developing countries which are characterized by low-income economies and low energy consumption per capita (Fig 0.2). Access to electricity and use of modern energy service are not available for the majority of the population, especially in rural areas. Although these countries are often rich in primary resources, these are rarely exploited at local level, moreover current energy systems are weak and characterised by low reliability.

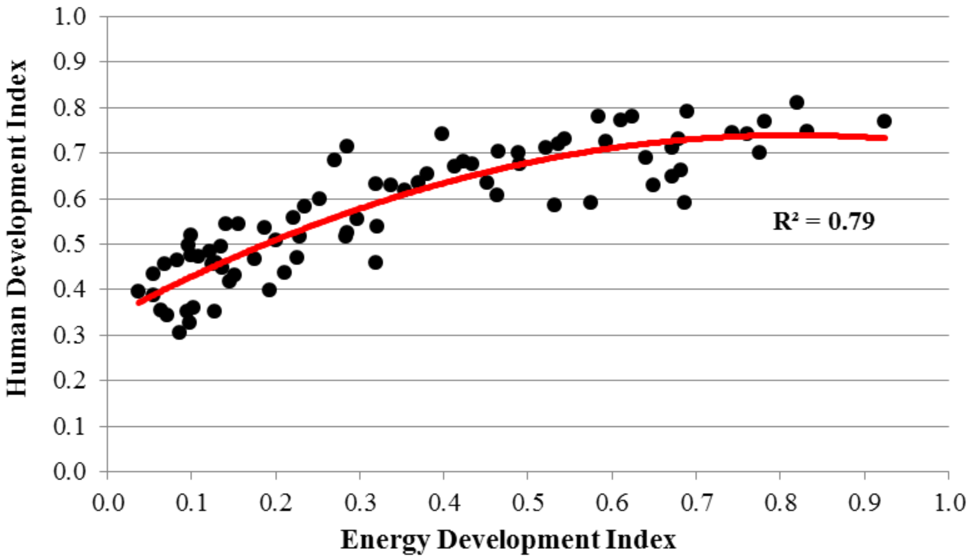


Fig 0.1 Comparison between HDI and EDI for 80 developing countries in 2012 [4].

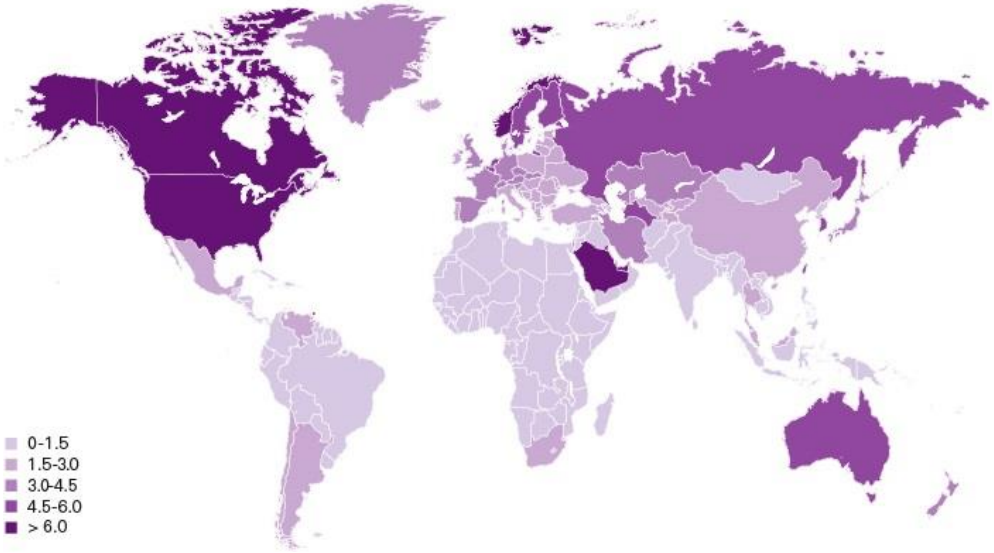


Fig 0.2 Total Primary energy consumption (2013) – TPES (tonnes oil equivalent per capita) [5].

The underdevelopment of the energy systems in the developing world can be highlighted also by considering the energy intensity (Fig 0.3) which explains how many tonnes of equivalent oil are necessary to produce 1$ of Gross National Income in purchase power parity. Africa with China, the Middle East and non-OECD Europe and Eurasia lead the classification with the highest values. Indeed energy intensity in developing countries is affected by underdevelopment of productive sectors and high conversion system inefficiencies.

In this context, appropriate energy strategies and appropriate technological solutions must not only be effective to solve these problems in the shortest possible time, but they must also face the issue from a perspective that includes the concept of sustainability in all its dimensions: economic, environmental and social. This statement acquires relevance looking at real problems in each of these dimensions:

- *Economic dimension*: as mentioned before in the developing countries the energy intensity remains well above what is recorded in developed countries. Thinking that the national incomes of this countries are a small percentages when compared to the richest nations and assuming that they will experience a general economic growth

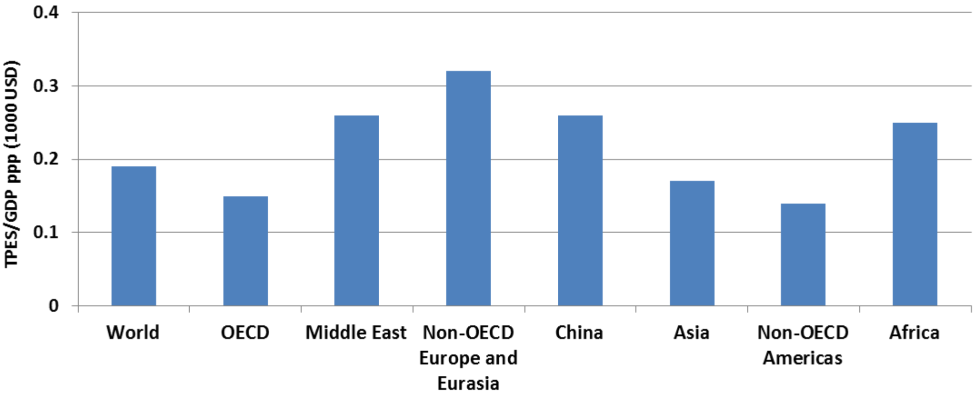


Fig 0.3 Energy intensity for the world's aggregated regions (2012) [6].

in the next decades, it is reasonable to expect a huge growth in the demand for primary energy. In this scenario, a technology based on fossil fuel may seem appropriate as it brings energy quickly where there was none before, but in the reality is not economically sustainable due to the rising price of an increasingly scarce resource. Diversification through technologies that take advantage of local resources, mainly renewables, can represent a viable solution.

- *Social dimension*: according to the world Health Organization, nowadays more than 1.4 million people die each year due to the effect of the smoke of cooking systems based on biomass such as the three-stones fire. Projections to 2030 [3] say that deaths from inhalation of smoke from biomass will be more than deaths from AIDS and Malaria combined together. Technologies are already available that can provide a solution to this problem like improved cook stoves, and domestic biogas systems. They are user friendly, easy to maintain and low cost.
- *Environmental dimension*: overuse of natural resources to obtain biomass or charcoal for basic needs like cooking or lighting has and will have an increasingly stronger impact on ecosystem and biodiversity. The shift toward technologies that use modern fuels (biogas, LPG, natural gas, electricity) is strongly required.

Fitting into these issues, an appropriate technology is a technology resulting from an *a-priori* analysis of the requirements and constraints of the targeted context. Nevertheless there is no technology right or wrong, but there always exists an integrated system of appropriate technologies that can better meet the needs, taking advantage of the resources already available in the respect of the territory, by providing proper energy supplies for end uses and services (Fig 0.4).

In addressing the issues of this framework, it is widely recognized that access to electricity is the main leverage for development. This aspect is also stressed in the calculation of the previously mentioned EDI, in which 2 of the 4 components make reference to electricity (share of population with access to electricity and per capita electricity consumption in the residential sector). The electric vector is the most established form of energy because it can catalyse the solution of many problems: from providing lighting at night giving the opportunity for young people to study, passing through the possibility to give better services (education, health, communication) and to satisfy electric needs in the domestic and productive sectors, up to improved access to information.

The fact is that today the distribution of electricity in the world is far from being fair. Table 0.1 makes clear the deep differences in the electrification rate around the globe. Data on energy access were collected for all 140 countries defined as developing

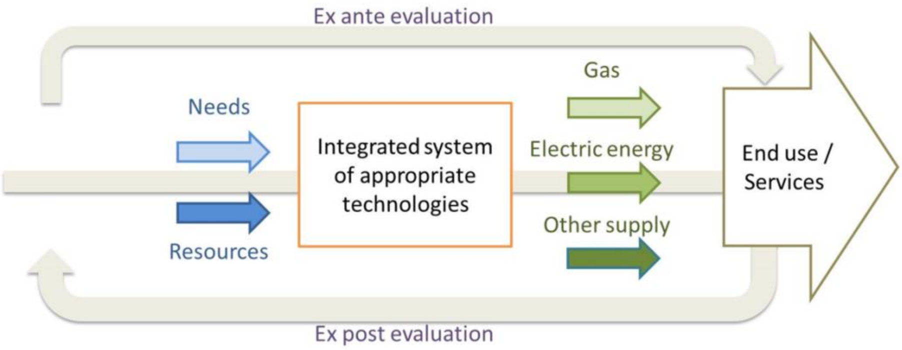


Fig 0.4 Appropriate technology scheme.

countries by UNDP (2007). Fifty of these countries were considered to be Least Developed Countries (LDCs) according to the UN's classification system (2007). Thirty-one of the LDCs are located in sub-Saharan Africa. In particular, focalizing the attention on developing country (Fig 0.5), it is evident that there is a distinct difference between the rural and urban level of electrification (Fig 0.6).

Table 0.1 Access to electricity in the World (2008). Author's elaboration based on [7].

Region/area	Total Population (million)	Electrification Rate	Total Population without electricity (million)
World	6692	78%	1456
OECD and Transition economies	1507	100%	3
Developing countries	5185	72%	1453
Least Developed Countries	824	21%	635
Sub-Saharan Africa	777	26%	561

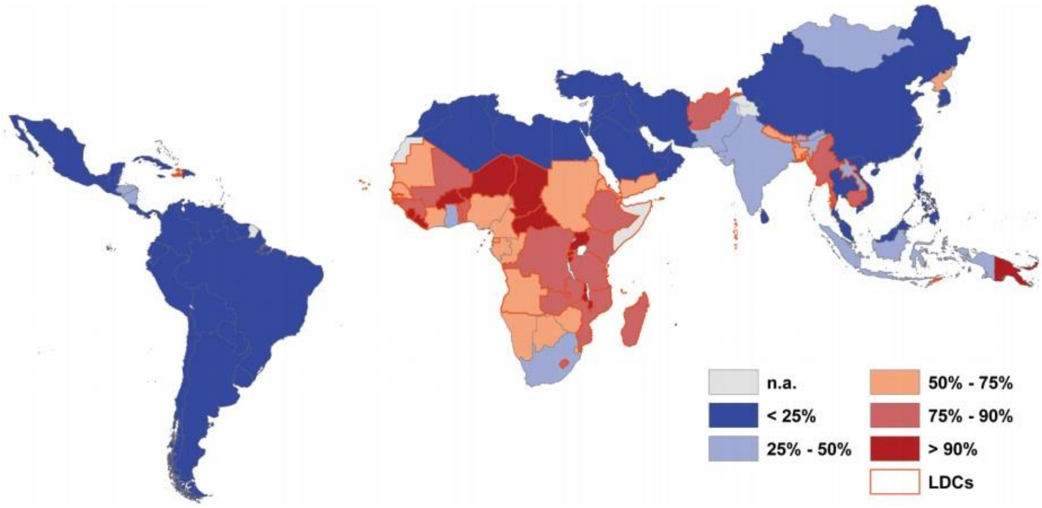


Fig 0.5 Share of people without electricity access for developing countries (2008) [7].

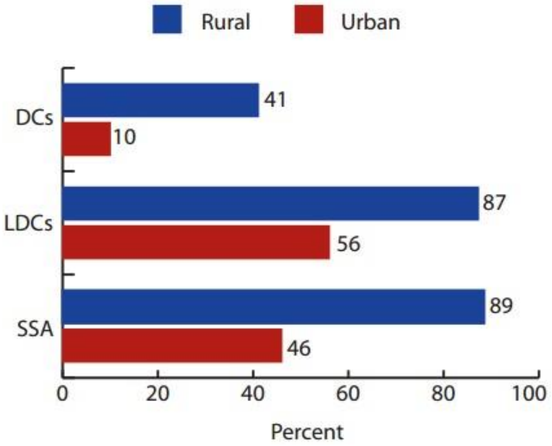


Fig 0.6 Share of population without electricity access in rural and urban areas for developing countries, LDCs and sub-Saharan African countries (2008) [7].

In light of the findings, policy makers in developing countries, with the help of international organizations, are giving much importance to electrification. As evidence of this, the World Energy Outlook 2012 [3] predicts an increase in the electrification rate in developing countries up to 85% in 2030. Access will increase mainly in urban areas, where providing electricity by extending the national grid may be easier. On the other side, the process of electrification of rural areas will be slower due to higher distance from the national grid, weaker fuel supply chains, weaker administration capacity, scattered villages and homesteads, etc.. In this case various options for supplying electricity need to be considered:

- Connection to the main-grid can provide a cheaper energy but the cost of extending the grid to sparsely populated areas can be very high and long distance transmission systems can have high technical losses [8].
- “Off-Main-Grid” decentralized technologies can provide electricity to rural communities, even though they require high investment costs [9]. Technologies of this solution can be divided in three categories:
    1. Home Based Systems: a system that supplies electric needs to a household. Optimal solution when there is a big dispersion of houses, the power source is installed closed to the load and the technology adopted is related to the context (mostly Solar Home Systems).
    2. Community and Small & Medium Enterprise Based Systems: which provide electric needs to a local service or to a local income activity.
    3. Micro-Grids: which address several consumers providing centralized electricity generation at the local level using a village distribution network, they can be based on:
        - Renewables: ranging from grids relying on a single source to micro-grids that can integrate more than one source of energy (hydro, biomass, wind and solar), they are characterized by an high investment and a low O&M costs being “fuel free”. The negative points are the strongly dependence on batteries to avoid blackouts and the not dispatchability of the produced energy.
        - Diesel Generators: characterized by a lower capital investment and higher O&M costs if compared with the renewables solution, they permit to give electricity when necessary but with the compromise of the noise and pollution they cause.
        - Hybrid Solutions: relying on renewable energy to generate most of the total supply, they present a genset as a backup in order to reduce the battery size. These options take the positive aspects of the previous configurations to give an optimized solution in terms of costs and quality of service.

A further comment to the process of electrification that developing countries may follow arises when considering the new approach of developed countries towards the electric system. Indeed, what is occurring now in the developed world is a slow shift from centralized systems to distributed systems and smart grids, with a great preponderance towards renewable resources. Thus, in countries where energy planning is still in its early stages, it would be smart to consider small scale decentralized systems mainly based on renewable energy as a viable alternative to the traditional centralized electric system based on fossil fuels. It is also true that problems such as the high investment costs and the inherent uncertainty of supply, with the associated problems of stability and management, make this route very rugged and certainly not viable without a strong political will, coupled with effective international support.

Despite of this, in the future, access to energy provided by renewable energy may be the only solutions in those situations where no other solutions are feasible. Indeed, access to energy supplied by renewable resources is giving its best results in those rural areas where the impossibility of extending the grid or the high costs of fuel supply makes renewables the only solution.

Among renewables, “Off-Main-Grid” Photovoltaic systems represent one of the most successful technologies in the developing world, especially for the resource availability, the extreme simplicity of application, the maturity of the technology and the availability on the market. This power technology, as known, converts the energy from the sun directly to electricity thanks to solar cells that are made with semiconductor-based materials. A number of solar cells are gathered together to form a solar panel and a number of solar panels can be combined in order to achieve the desired output capacity. This fact gives to this technology a high degree of modularity making it suitable for a different range of applications. Thanks to these strengths, the “Off-Main-Grid” Photovoltaic technology is spreading strongly in developing world, and example is given through the case of Uganda (shown in Fig 0.7).

“Off-Main-Grid” Photovoltaic Systems can be classified [10] into two categories:

1. Stand-Alone Photovoltaic (SAPV) systems: which are systems the purpose of which is to meet the needs of an individual customer, be it a person, a household or a business activity. According to the size is possible to distinguish:
   - Pico Solar Systems: are defined as small solar systems, normally portables, with a power output of 1–10 W, mainly used for lighting and capable to replace lighting sources such as kerosene lamps and candles.
   - Solar Home Systems (SHS): generally cover the consumption of typical households, with a power output up to some hundred Watts (Fig 0.8).
   - Community Based Systems: which are larger SAPV systems that provide energy to community services such as health centres, schools, factories, with a typical range from some hundred to some thousand Watts output power.
2. PV Micro-Grid: which are systems that can supply the needs of a number of households and community services. In this case solar panels are assembled in the range of some hundreds of kW and a distribution network provides the electricity to the connected loads.

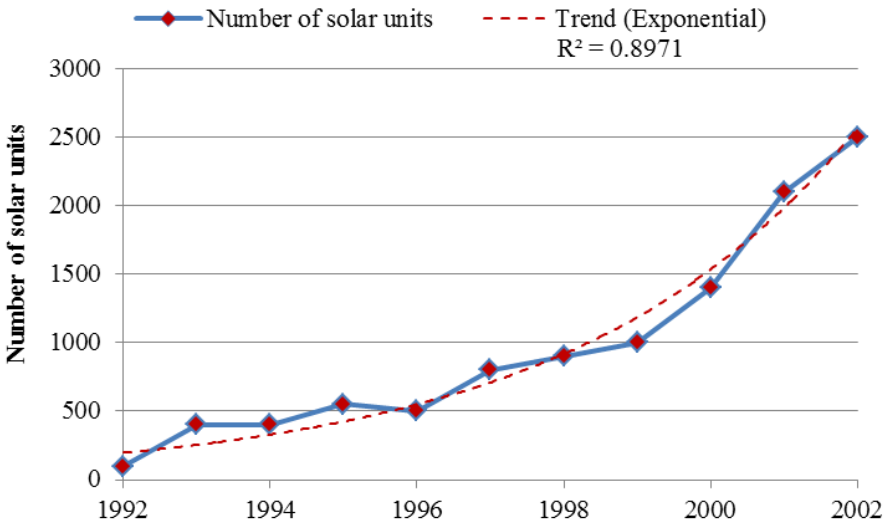


Fig 0.7 Number of solar units disseminated in Uganda (1992 – 2002) [11].

Fig 0.8 Examples of SHS in Uganda, East Africa.

The SAPV systems, as already mentioned above, are now widespread in LDCs, thanks to the fact that now the technology is well established and frequently such products, especially the Pico Solar Systems, are imported easily from abroad. In most cases the introduction of an SAPV system happens thanks to support development projects by NGOs or international institutions, as it completely lacks the support of local authorities. However, in recent years are also increasing the activity of local private enterprises that, finding business opportunities, provide standard products and in some cases installs SAPV systems (Fig 0.9). Concerning the PV Micro-Grid there are few application examples that, in most of the cases, are experimental projects related to development projects. Nevertheless PV Micro-Grid, having the aim to reach a significant number of users, should instead be addressed with higher attention by the local authorities who can evaluate the possibility of installing such systems to compensate the lack and weakness of the national grid.

In conclusion, given the general framework related to electrification exposed in the previous pages and focusing on the “Off-Main-Grid” PV technologies options, there is a best selection that best meet local needs depending on the particular local context. Moreover, once the specific option has been identified, a further important step is to employ an appropriate method to size the system components in order to best fit the system to the local targeted context.

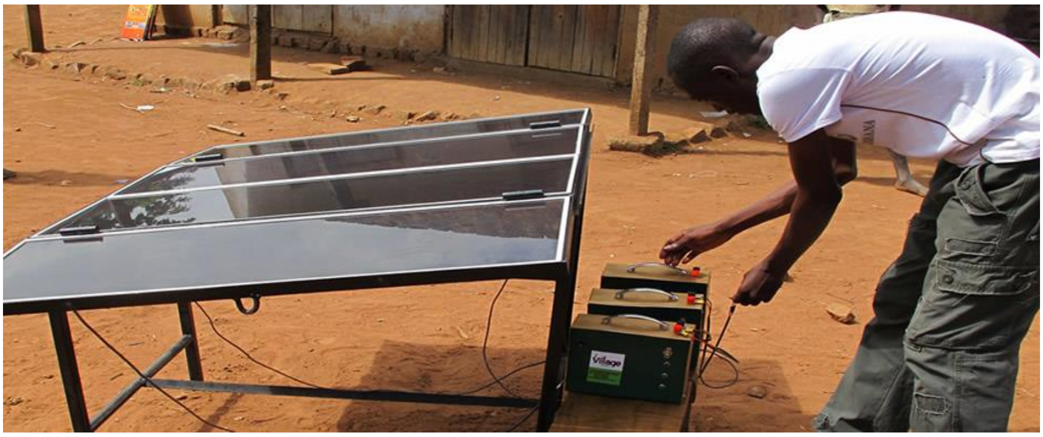


Fig 0.9 Examples of SAPV system installed by Village Energy Uganda Ltd.

In this work “Off-Main-Grid” Photovoltaic Systems are deeply investigated with particular attention to appropriate sizing methods for SAPV systems and PV Micro-Grid in developing countries. SAPV systems are discussed thanks to the author’s experience on the field during the internship period of two months at Village Energy Uganda Ltd. During this period it was possible to analyse the context of Uganda and study the techno-economic approach of the company in order to develop an appropriate practical context-based sizing tool. On the other hand, the PV Micro-Grid matter has been addressed with an academic and scientific view through a critical assessment of the scientific literature with the aim to suggest a more appropriate sizing methodology for real-context based application in developing countries.

In Chap.1 a comprehensive analysis of Uganda is exposed with particular attention on the energy issue in order to give to the readers an overview of the context under consideration. The business activities of Village Energy Uganda Ltd, one of the Ugandan actors in small Stand-Alone Photovoltaic systems installation, is also exposed lingering briefly on the existing problems and the solution found and left by the author during his internship period of two months.

In Chap. 2 the “Off-Main-Grid” Photovoltaic systems are deeply investigated through a review of the sizing methodologies developed in the scientific literature and the most common software available. In the first section, the technology that characterizes these systems is exposed through an essential analysis of each component. Then, the main layouts are presented in order to identify the differences in applications. Finally the sizing methodologies are investigated. Specifically, two sizing methods available in the scientific literature, namely the intuitive and numerical method, and the commercial software *HOMER* are described in details, since they are implemented and applied in subsequent chapters.

In Chap. 3 the activities carried out by the author during his internship period of two months at Village Energy Limited in Uganda is presented. After a brief introduction that explains the motivations of the work, the decision support tool developed by the author, named *VE Sizing&Pricing* tool, is exposed as a context-based appropriate intuitive method to size SAPV systems. Finally a typical case study is chosen and the design results are compared with those computed with the software *HOMER*.

In Chap. 4 the PV Micro-grid solution for rural or peri-urban electrification is taken into consideration. After the motivations that have lead the investigation, the numerical model implemented in MATLAB® is exposed highlighting the new features introduced in order to develop an appropriate numerical PV Micro-Grid sizing method for real-context based application in developing countries. Finally a case of study based on the Ugandan context is chosen and a results’ comparison with those computed with intuitive method and the software *HOMER* is proposed.

Chapter 1

1. Uganda and Village Energy Ltd

The main objective of this chapter is to introduce the Ugandan context focusing on the analysis of the energy situation and with particular attention to solar resource. At the end of the chapter, the business activities of Village Energy Uganda Ltd, one of the Ugandan actors in small Stand-Alone Photovoltaic systems installation, is also exposed lingering briefly on the existing problems and the solution found and left by the author during his internship period of two months.

1.1 Background

Uganda is situated to the extreme west of East Africa (Fig 1.1), with no outlet to the sea (but facing the second largest lake in the world, Lake Victoria). Beginning in the late 1800s, the area was ruled as a colony by the British, who established a protectorate. Uganda gained independence from Britain on 9 October 1962 maintaining its Commonwealth membership. The capital and largest city is Kampala.

The current President of Uganda is Yoweri Kaguta Museveni, who came to power in a coup in 1986. Museveni was involved in the war that deposed Idi Amin Dada, ending his rule in 1979, and in the rebellion that subsequently led to the demise of the Milton Obote regime in 1985. Parallels have been drawn between Museveni and his predecessors and now Uganda is considered to be in a sort of hidden dictatorship.

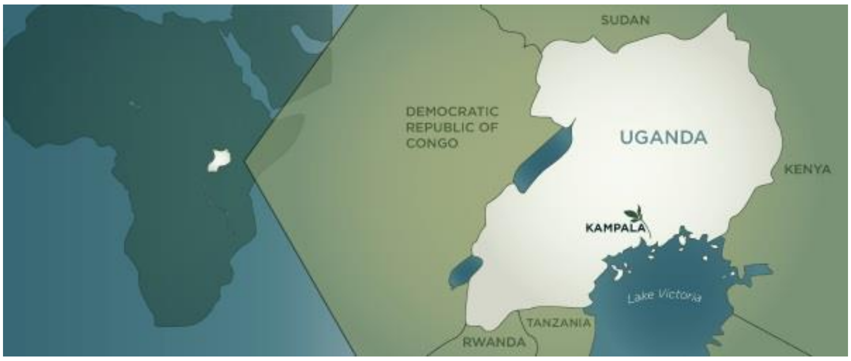


Fig 1.1 Geographical position of Uganda.

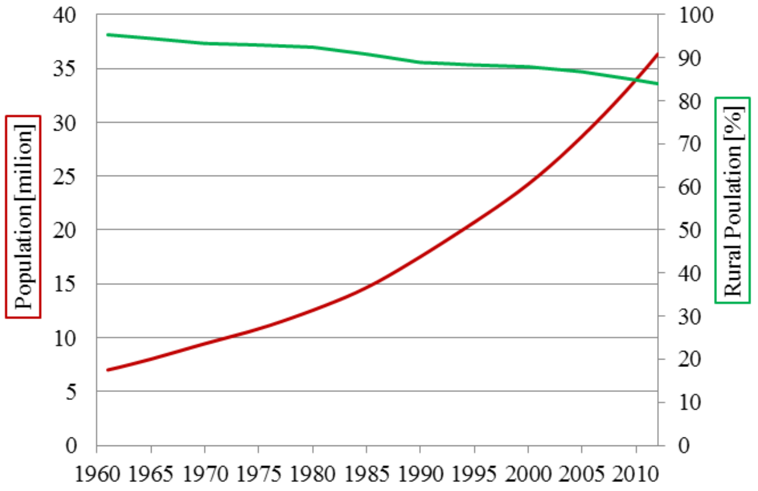


Fig 1.2 Trend of total population and rural population. Author's elaboration based on [12].

As shown in Fig 1.2 Ugandan population is growing exponentially and is slowly moving into the cities during the last 50 years. Nowadays Uganda has an estimated total population of 36.3 million people and a growth rate of 3.4% per year.

According with the World Bank ranking by means of Gross National Income per capita [12] Uganda in 2010 was at the 11th place of the poorest countries in the world with 37.7% of the population living on less than $1.25 a day. Uganda is at the 161th place out of 186 in the UNDP Human Development Index ranking [13] and it is part of the 34 African countries appearing on the UN list of the LDCs. The reasons of this persistent decline are to be found (i) in two decades of civil wars, (ii) in an inconsistent management and a chronic political inability to plan over the long term, and (iii) in the extent of country's foreign debt. In 2006 Uganda was admitted to a reduction of the 100% of its debt with great benefit of the entire economic system. This fact, joined with a period of relative macroeconomic and political stability, especially since the end of the armed conflict in Northern Uganda in the mid-2000s, has produced an economical growing over the last years that seems to be really sustained. However, this growth is resized down, in absolute values, if compared with the data coming from the sub-Saharan area. Indeed Table 1.1 shows that GNI per capita in 2011 was about half of the average of the surrounding sub-Saharan countries.

Despite this situation if we look at the Human Development Index Uganda is not far from the average of its region. The reasons are to be found in the deep reforms especially in health and education sectors, which have characterized the last 20 years. Reforms, which were strongly demanded by international organizations as a condition for continuing to support Uganda with economic aids. In particular expected years of schooling received a boost in 1997 when free primary and part of secondary education

Table 1.1 Comparison of development indicators (2011). Author's elaboration based on [12].

Country/Region	**GNI per capita (2005 PPP$)**	**GDP Growth**	**HDI**
World	10134	1.8 %	0.692
Sub-Saharan Africa (developing only)	1919	1.8 %	0.472
Uganda	1087	4.6 %	0.454
OECD (high income)	34553	1.4 %	0.904
Italy	26922	- 0.1 %	0.881

Table 1.2 HDI indicators. Author's elaboration based on [13].

	Life expectancy at birth	**Expected years of schooling**	**Means years of schooling**	**GNI per capita (2005 PPP$)**	**HDI**
1985	49.6	5.6	2.3	520	0.3
1990	47.4	5.6	2.8	554	0.306
1995	44.9	5.5	3.4	664	0.316
2000	46.1	10.7	3.9	755	0.375
2005	50.2	10.4	4.3	880	0.408
2010	53.7	11.1	4.7	1126	0.45
2011	54.1	11.1	4.7	1158	0.454

was made available for four children per family. However only some of primary school graduates go on to take any form of secondary education and this reflects in a non-substantial increase in the means years of schooling, as shown in Table 1.2. Concerning the life expectancy at birth the reversal of negative trend is due to progress in health. For example Uganda's elimination of user fees at state health facilities in 2001 has resulted in an 80% increase in visits, over half of this increase is from the poorest 20% of the population. Moreover, Uganda has been among the rare HIV success stories. In the 1980s, more than 30% of Ugandan residents had HIV; thanks to a vigorous battle during the ‘90ies this had fallen to 6.4% by the end of 2008.

Since 1986, the government has acted to reform productive sectors devastated during the regime of Idi Amin and the subsequent civil war. Fig 1.3-A represents that, while agriculture accounted for 56% of the economy in 1986, it has now been surpassed by the services, which nowadays contributes almost half of the entire GDP. The growth of this sector is principally due to the development of telecommunications and tourism over the last decade. However, the majority of the workers are still employed in the agriculture sector (Fig 1.3-B), which now contributes for only the 23% of the GDP despite that Uganda remains one of the country with the most fertile soils of the world. Recognizing the need for increased external support, Uganda negotiated a policy framework paper with the IMF and the World Bank in 1987. It subsequently began implementing economic policies designed to restore price stability and sustainable balance of payments. While these policies produced positive results on inflation that passes from the 200% in the eighties up to values of a single digit in the first decade of the new century, the country's trade deficit continued to deteriorate during the years. In 2011 Uganda registered a trade deficit of € 2.39 billion (Table 1.3).

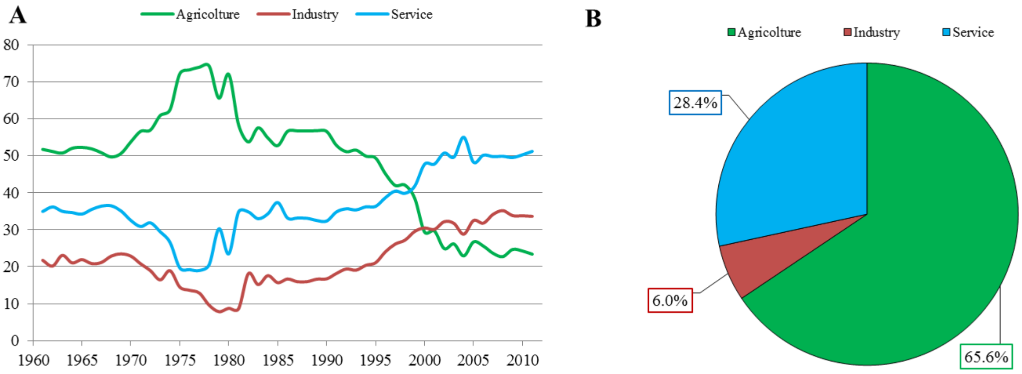


Fig 1.3 Analysis of the 3 economic sectors: Value added (% of GDP) (A), and workers' distribution (2011) (B). Author's elaboration based on [12].

Table 1.3 Formal exports and imports by percentage value (2011) [14].

Major Exports		**Major Imports**	
Coffee	17.5%	Petroleum and petroleum products	17.5%
Fish and fish products	7.9%	Road vehicles	7.9%
Cellular Phones	4.9%	Machinery for specialized industries	4.9%
Petroleum products	4.5%	Iron and steel	4.5%
Cement	4.4%	Telecommunications instruments	4.4%
Tea	4.2%	Medical and pharmaceuticals	4.2%
Tobacco	4.2%	Cereals and cereals preparations	4.2%
Total export revenue	**€ 1.25 billion**	**Total import bill**	**€ 3.64 billion**

1.2 Overall status of energy sector in Uganda

Data about the Uganda energy sector are limited and not complete since Uganda is not part of the countries that provide information to the International Energy Agency. The following analyses are based on data provided (i) by the Ugandan Ministry of Energy and Mineral Development and (ii) by the U.S. Energy Information Administration. In the latter case, biomass is not considered since it is not accounted in any trade (i.e. in the cases of developing countries, biomass refers to the *traditional biomass*: firewood, animal waste, agriculture waste, etc. that local population collects and sometimes trades locally and informally). Therefore, in order to compute indicators trends and make comparisons with other countries and world regions, a 90% of biomass incidence is assumed by the author. That share is in line with the value of neighbouring countries with similar GDP.

Fig 1.4 shows diagram balance for the country energy balance of 2011 (the complete table balance is in Appendix A). Energy supply is predominated by biomass, electricity and oil products are also used, but contribute less than 10% of the Total Primary energy Supply (TPES). While oil reserves have been discovered, there has been no local production and Uganda imports all of its oil [15]. High transportation costs make the price of imported fuels expensive relative to per capita income.

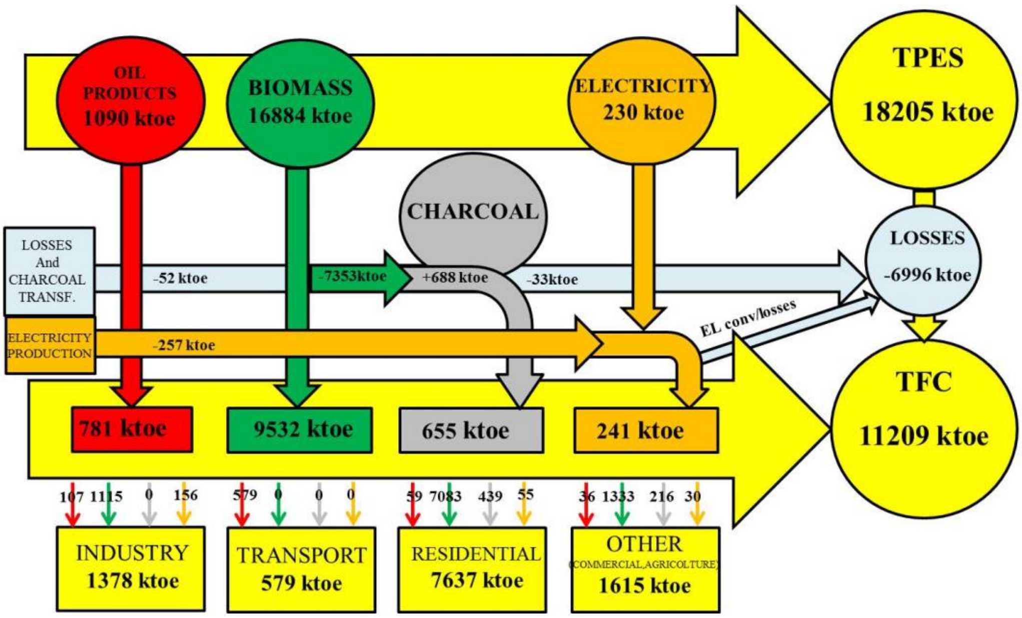


Fig 1.4 Ugandan energy balance for the year 2011. Author’s elaboration based on [16].

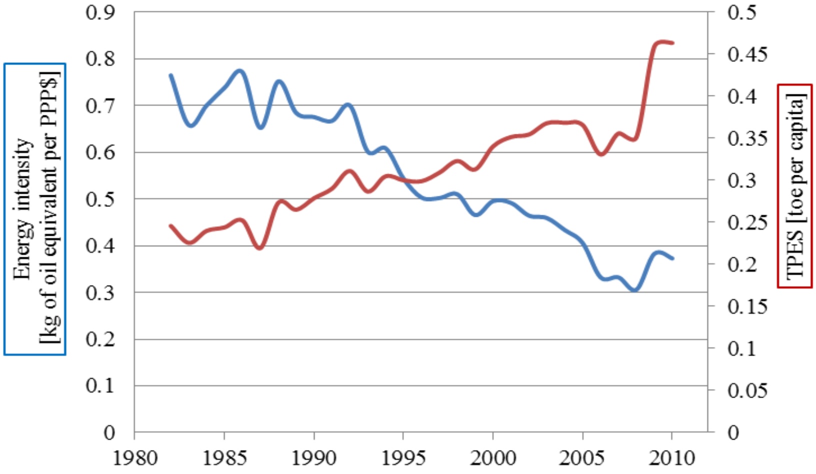


Fig 1.5 Trend of Energy Intensity and Total Primary Energy Supply per capita. Author's elaboration based on [15].

Moving to the Total Final Consumption (TFC), as it happens in most of the other LDCs, the biomass energy is used for cooking and heating in households, commercial and public institutions and in small scale industries. Thus, biomass remains the most important source of energy providing for 85% of the TFC, in form of firewood and crop residues, representing one of Africa's highest values. In the passage between supply and consumption nearly 45% of this biomass is converted into charcoal with a conversion efficiency of less than 10%. This practice serves to support urban households that predominantly use charcoal while pure biomass is principally used in rural context. After the conversion, biomass and charcoal are used for the 75% in the residential context. Concerning oil products, they are used transversally into the Ugandan economy but mostly (75%) to sustain the transport sector. Oil, for the 25% of the total imported, contributes also to generate electricity, especially in the regions not served by the national grid.

To better understand the energy issue in the country is worthwhile to focus the attention also on the trend data of two important indicators: the Total Primary Energy Supply per capita and the Energy Intensity (Fig 1.5). About the latest one, is set to high average values during the last 20 years, 2 times higher than the world average. The explanation certainly lies in the lack of efficiency of an economy based on the use of biomass. Concerning the Uganda's per capita energy supply has nearly doubled in the past 30 years, remaining however well below the world average and also below the sub-Saharan mean (Table 1.4). Considering that the population has nearly tripled in the same period (from 13.5 million in 1982 to 36.3 million today) we can deduce that nowadays the primary energy supply of the country is six times the one in the eighties.

Table 1.4 Comparison of energy indicators (2010). Author's elaboration based on [12].

Country/Region	**Energy intensity [koe per PPP$]**	**TPES [toe per capita]**
World	0.161	1.890
Sub-Saharan Africa (developing only)	0.278	0.682
Uganda	0.373	0.463
OECD (high income)	0.130	4.665
Italy	0.088	2.604

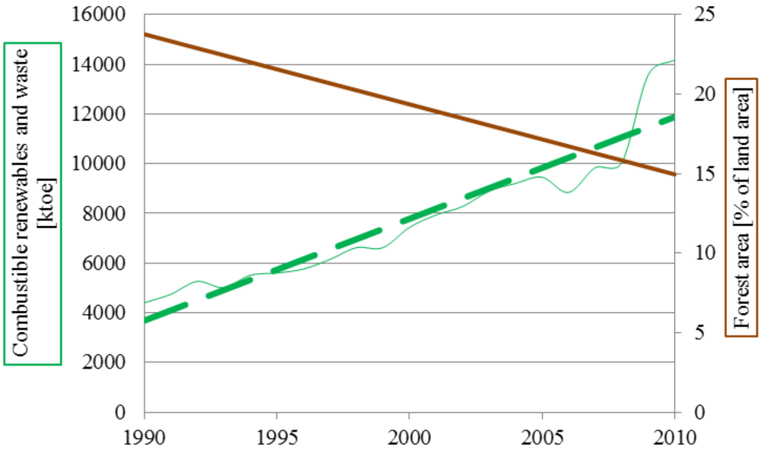


Fig 1.6 Depletion of forest versus biomass usage. Author's elaboration based on [12] and [15].

The growing demand for primary energy, combined with the need for more arable land to support the food needs of a population that grows exponentially, has the consequence an increasing deforestation. The fact that the primary energy demand is met almost entirely through the use of biomass that, with regard to the woody part, comes largely from the forests of the country, contributes to the process of deforestation. Today less than 15% of Uganda's land area is covered with forest (Fig 1.6) and deforestation continues at a rate of 3% in the last years, leading to fuel wood scarcity in rural areas and an increase in price levels of charcoal in urban areas.

1.3 Electricity access in Uganda

80% (29 million) of Uganda's people do not have access to electricity (Fig 1.7). This, coupled with an electricity demand growth of 7-8% per year, brings pressure on the energy sector.

Fig 1.7 Slums with no access to electricity in a peri-urban area of Kampala.

Annual electricity consumption per capita is 64.5 kWh, which is about 11% of the African average and 2,5% of the world average [17]. About 72% of the total grid supplied electricity is consumed by 12% of the domestic population concentrated in the Kampala metropolitan area, and the nearby towns of Entebbe and Jinja.

As represented in Fig 1.8 there is no relation between the increasing of the electricity demand and the power availability unless in the last years in which is evident that the electric power consumption follows the evolution of the installed capacity. Ugandan authorities together with private companies have approximately doubled the installed capacity over the last 30 years. The fact is that these investments today are inadequate since Uganda's power sector is suffering from a shortage of generating capacity. Energy demand, although small when compared to developed economies, far exceeds the supply and the power deficit is currently estimated at 130 MW. Nowadays there are 539 MW of power installed of which the 65% are represented by hydropower plants (Table 1.5), the rest of electricity is produced in hot fuel oil generators in order to provide the electricity needs of the urban towns in the northern region, where the national grid has so far not been extended. There is also a small contribution from bagasse, a biofuel that remains after sugarcane or sorghum are crushed to extract their juice. Regarding electricity distribution from the national grid, it is far from being reliable since blackouts are at daily occurrence. Furthermore, data from the Ministry of Energy and Mineral Development say that the electrification rate is only at the 12% on national base (the remaining 8% to reach the 20% of people with access to electricity mentioned before makes use of diesel generators or other off-grid systems) and only 2% in the rural areas. This scenario leads two main problems:

- 95% of rural households have no access to electricity and use traditional lighting technologies [18]. These include kerosene lamps that give poor quality lighting and emit toxic smokes and representing a healthcare hazard for small children especially.
- The effort to transform Uganda from agricultural country to industrial country remains severely limited by the chronic shortage of electricity. In the rural context new businesses that require electricity are discouraged and companies already existing are forced to buy diesel or petrol generators that are costly to operate and have negative environmental impacts.

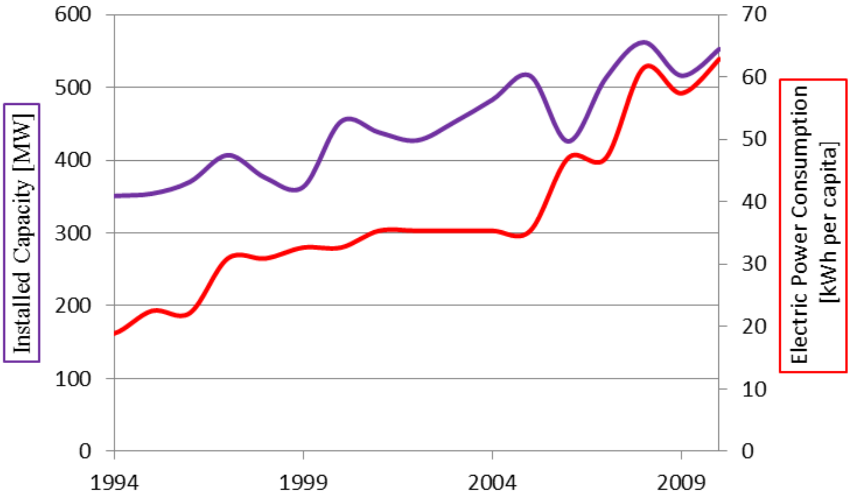


Fig 1.8 Installed Capacity versus Electric Power Consumption. Author’s elaboration based on [12] and [15].

Table 1.5 Installed electricity capacity (MW), 2008-2010 [19].

Plant Name	**2008**	**2009**	**2010**
Hydro Electricity	**315**	**328**	**352.5**
Kiira	120	120	120
Nalubale	180	180	180
Kasese Cobalt	10	10	10
Kilembe Mines	5	5	5
Kilembe Tronder Power	-	13	13
Mpanga	-	-	18
Isahaha Ecopower	-	-	6.5
Thermal Electricity	**200**	**150**	**170**
Lugogo	50	-	-
electromax	-	-	20
Kiira	50	50	50
Jacobsen Plant - Namanve	50	50	-
Mutundwe	50	50	-
Ida Plant	-	-	50
Aggreko II	-	-	50
Bagasse Electricity	**12**	**14**	**17**
Kakira	12	12	12
Kinyara	-	2	5
Installed Capacity [MW]	**527**	**492**	**539.5**

To solve this problems the government is planning to install more power capacity (3 big hydropower plants are under construction), joining this activity with the extension of the national grid.

1.4 Solar energy in Uganda

Uganda is located along the equator and receives a high level of solar insolation for more than 8 hours of sunshine per day all year round. The incident radiation is estimated to be between 5–6 kWh/m^2/day. For that reason solar “Off-Main-Grid” solutions represent a great opportunity for rural electrification. Some authors [20] found out that, solar energy sources were hardly used in Uganda and that there were at least 540 PV installations in the country, which by 1995, had amounted to a total capacity of about 152.5 kW. Today however, the number of solar units in the country can be estimated to be more than 11,000 PV installations with a total capacity of about 3 MW and is slowly spreading in the rural areas. The Solar Home Systems (SHS) represents the biggest market (Fig 1.9) and the largest demand is for PV systems ranging from 10-50 W. Field verifications found that significant portion of grid-connected consumers also utilize solar PV systems in their homes and businesses as backup.

Nowadays the Ugandan market is flooded by an infinite number of solar products. In the range of pico-PV size, the Chinese products have monopolized the market due to their extremely low price, leaving no space for competitors. However, the quality is so low that people are now realizing that is better to spend some money more to have a product that lasts longer. Focusing on SHS size, a lot of small and medium business realities are active in creating standardize products that are able to intercept costumer needs, the majority of these companies are not located in Uganda but they have only a sales unit while the headquarter is in another country. There are companies from all over the world, obviously some from China and India (with the most competitive price)

Fig 1.9 A Solar Home System (Musana 500) installed in Soroti by Village Energy Uganda Ltd.

but also from Australia, Europe and USA whose aim is to bring electricity in developing countries. In the last case the products are designed in the developed country and produced in Asian countries for having a good final price, then are imported in Uganda market to be only sold.

In this extremely full market there is little space for local enterprise. The only quote of the market left uncovered by foreign companies is represented by customized solar systems.

In Section 1.5 the reality of Village Energy Uganda Ltd, a local enterprise, is exposed through the author's experience as an internship student for the period of two months, from the 14th of October to 13th of December 2013. During this period it was possible to analyse the context of PV in Uganda and study the techno-economic approach of Village Energy Uganda Ltd to better understand the potential of Stand-Alone Photovoltaic systems in developing countries.

1.5 Village Energy Uganda Ltd

Village Energy Uganda Ltd [21] works to provide solar based energy solutions to off-grid households, small businesses and communities in Uganda. The company was founded in 2008 by the vision "*better energy – better communities*" of Abu Musuuza and Roey Rosenblith. These men helped by Steven Muwanguzi, a gardener with the hobby of electronics, who find the way to create the first product (the Musana 100), decided to focus on solar energy to start a new business activity. The mission of the company is to increase access to affordable renewable energy, first for Ugandans, then for East Africans and eventually for the developing world at large. Through innovative solar technologies, the aim is to bring social services and stimulate economies to rural and peri-urban communities, where such services did not exist, by providing the opportunity to improve their social, economic and environmental lifestyles.

Fig 1.10 Village Energy members at Kampala Office. From the left side: Shevika, Shafik, Abu, Paola, Suleiman, Frank, me and Steven.

Since its inception in 2009, Village Energy has provided over 4500 solar systems in 15 districts of Uganda. The head office is based in Kampala (Fig 1.10) with a regional office in Soroti. The company is composed by 8 employees, 6 technicians and 2 accountants led by 3 managers among which a clever Italian physicist. The strength of Village Energy is to be able to show off products assembled in Uganda by Ugandan employees. However, the *made in Uganda* brand is not winning because is a drop in the ocean of endless companies that import finished low-cost products from abroad putting a strain on the survival of companies such as Village Energy.

Standardized and customised Products

As was investigated by Village Energy the average rural household lives off subsistence farming. Typically such a household spends about 30,000.00 Ugandan Shillings (9 €, assuming the exchange rate of about 3,500.00 UGX/€) a month on kerosene for lighting and travel long distances to recharge their cell phones. These costs represent about 15% of their income. If these households invested in a 10-30 W solar system, they would amortize the capital costs within a year period and reduce their energy costs to 4% of their income for the following year. The 4% reflect the cost of replacing the batteries every year, which is the only maintenance required to make these systems last 3-5 years. Aside from the savings, a solar household system will provide significantly better and healthy lighting and reliable phone charging. “Middle class” rural households, small businesses and institution such as school and hospitals operating in rural areas currently use gas or diesel generators to power up. Depending on the consumption of the appliances, these households and business spend between 200,000.00 UGX (57 €) and 500,000.00 UGX (143 €) a month. A capital investment of 2-8 million shillings (550-2200 €) for a solar system in the range between 100 W and 1000 W would be repaid within two years and provide large savings for the next 10 years with battery replacement every 3 years.

Fig 1.11 A student from Gulu's primary school with a freedom light donated by Village Energy and the musana 100 plug-and-play system.

Starting from the above information Village Energy has developed standardized products to address of different costumers' categories:

- Portable system: Freedom Light and Musana 100;
- Small rural Household: Musana range;
- Medium rural Household: Entertainment systems;
- Business solution: Phone charging system;

All the Systems are in direct current at 12 Volts and they are composed by 3 principal components: panel, battery and charge controller.

The Freedom Light is a rechargeable, solar powered, LED lantern (**Fig 1.11**) that is perfect for reading and studying during the night. This lantern replaces kerosene light. It has a lighting time of 5 hours on full charge and requires 8 hours charging time in direct sunlight, it has inside a small built in charge controller and power switch.

Musana 100 is a plug and play system consists of a 10 W PV panel and the green box shown in **Fig 1.11** that contains a 7 Ah lead-acid battery and a built-in charge controller. The system allows having 3 bright LED lights for 6 hours and comes with a multiple pins set to charge one phone. The Musana 100 is flexible in the sense that the included wires permit to move the lights from a place to another place according to customer's needs.

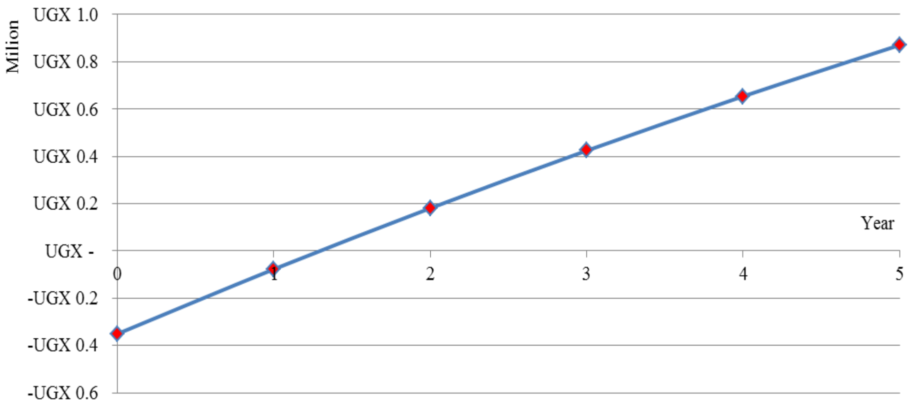


Fig 1.12 Return on Investment for Musana 100.

Table 1.6 The Musana Systems and Entertainment Systems characteristics.

Feature	**Musana 500**	**Musana 1000**	**Ent. Syst. 1**	**Ent. Syst. 2**	**Ent. Syst. 3**
Solar Panel	20 W	30 W	60 W	70 W	80 W
Lead-acid Battery	18 Ah	24 Ah	50 Ah	50 Ah	70 Ah
Charge Controller	5 A	5 A	20 A	20 A	30 A
LED lights	4	8	4	8	8
Phone charger	yes	yes	yes	yes	yes
Television	no	no	14”	14”	20”
Price [UGX]	**654,000**	**947,000**	**2,014,000**	**2,243,000**	**2,865,000**

By reconsidering data exposed at the start of the paragraph and recognising that Musana 100 gives a response to basic needs of the average rural households in terms of clean source of lights and the possibility to charge the phone without travel long distances, it is possible to give a return on the investment on a lifecycle of 5 years for a family that decide to buy this product. Given the cost of the system of about 350,000.00 UGX which represent the 20% of the total yearly income of the average rural household in Uganda, and assuming an yearly replacement of the battery inside the box and a real interest rate of 6%, the break-even point is located at the start of the second year (Fig 1.12) and the Net Present Value at the fifth year is around 800,000.00 UGX (50% of the total yearly income).

The investment is therefore convenient for both health (no more kerosene lamps for the next five years) and from the economic point of view. The main obstacle is the cost of initial investment that is out of the economic possibilities of the majority of rural households.

Musana systems and entertainment systems are designed to meet the needs of rural families by providing various solutions that intercept the budget of each customer (Fig 1.9). The characteristics and prices of all the systems are shown in Table 1.6.

Village Energy’s phone charging systems (Fig 1.13) have the capacity to charge up to 30 phones per day. The product comes with a 50 W panel 1 light and Mobile phone charging units comprehensive of a built-in charge controller, one 18 Ah lead-acid battery, 10 double-ended phone charging pins and an adapter for USB and micro USB. The owner of this system has the potential to earn 450,000.00 UGX (130 €) per month.

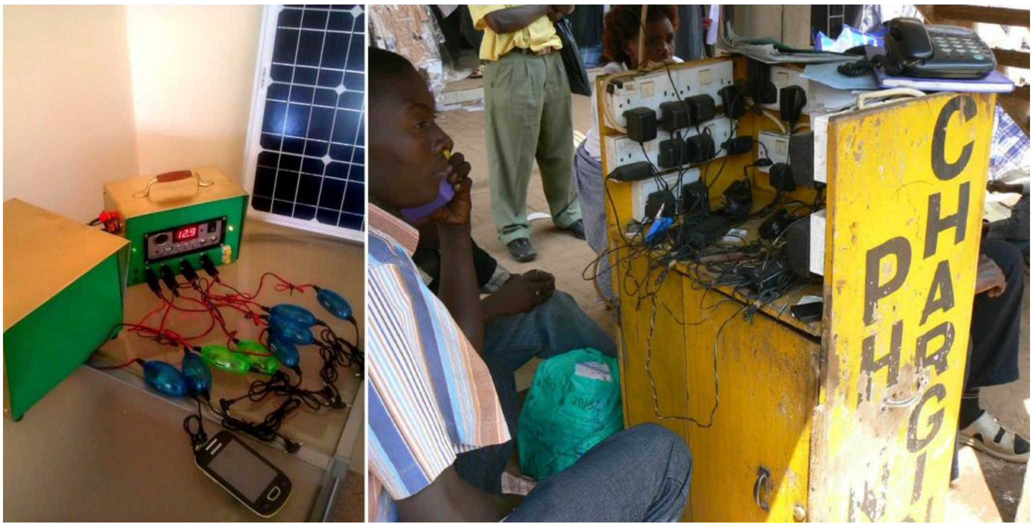


Fig 1.13 Village Energy phone charging system on the left and a typical phone charging business in rural context on the right.

Fig 1.14 Customized system installed for Lira’s secondary school in November 2013.

Village Energy is able to offer also customised solutions in order to perfectly meet the client’s needs. Solar solutions for bigger households, small business activities, public institutions such as schools and health care centres and in general non-conventional clients are representing the new market in which Village Energy can make the difference, being rooted in the Ugandan context.

Installation and Maintenance

All the final prices of the products that need to be installed on the client’s site have included also the stuff necessary for the system’s installation such as wires, plugs, molded boxes, connectors and, when required especially in big systems, an additional inverter for supplying AC loads.

Installation costs are also included (in many others case the client can only buy the stuff and is leaving alone to put them togheter). Village Energy’s technicians go to the client’s site to install the system (Fig 1.14) and in case something goes wrong (within the warrantee period), they will come back to the site and repair the system. All the systems come with a warranty of 6-12 months (depending on the product). After the warranty expires client can purchase a service package to continue to have Village Energy maintain his system.

Components on the market

As mentioned before Village Energy tries to assemble locally the components they purchase from the best quality-price vendors in Kampala. During the internship period a market survey was conducted by the author in order to comprehend the context and understand the room for improvement of Village Energy in such market. A large number of vendors were visited by the author’s and all the data collected are presented in the next figures.

In Fig 1.15 the PV panels' prices are exposed. The two technologies available on the market are the monocrystalline one at a specific price for power installed of approximately 3,500.00 UGX/W (1 €/W) and the poly-crystalline one that, as known, presents a lower specific price but also a lower productivity at the price of 3,000.00 UGX/W (0.86 €/W).

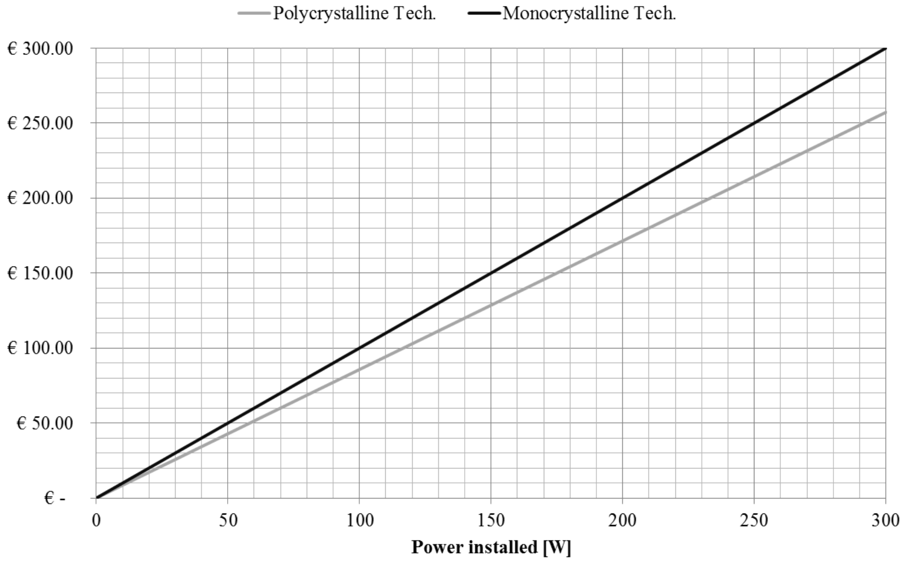


Fig 1.15 Price of PV modules resulting from author's elaboration after market survey.

In Fig 1.16 the batteries' prices are exposed. The technology is the lead-acid one, optimized for PV-DC applications at 12 Volts. Other better technologies are poorly available on the market due to the high prices that make them uncompetitive. Analysing the data it can be concluded that a linear relation exists and a specific price for energy installed of 490.00 UGX/Wh (0.14 €/Wh) can be assumed.

Finally in Fig 1.17 the charge controller's prices are exposed. In this case is not possible to extrapolate an overall trend because the differences on the market are substantial. However, a sharp look is able to distinguish 3 different trends. The bottom one is for the PWM (*Pulse Width Modulator*) analogic technology which is the cheapest one at a specific price for maximum ampere accepted of 7,000.00 UGX/A (2 €/A), the one in the middle is for the PWM digital technology available at 28,000.00 UGX/A (8 €/A) and the upper one is for the MPPT (*Maximum Power Point Tracker*) technology which is very uncommon and too much expensive if installed on small applications, at the specific price is 56,000.00 UGX/A (16 €/A).

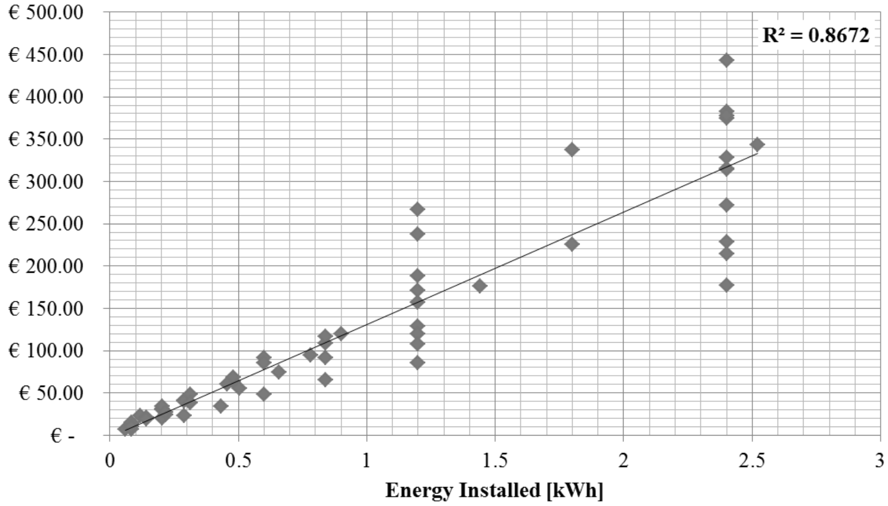


Fig 1.16 Price of Battery resulting from author's elaboration after market survey.

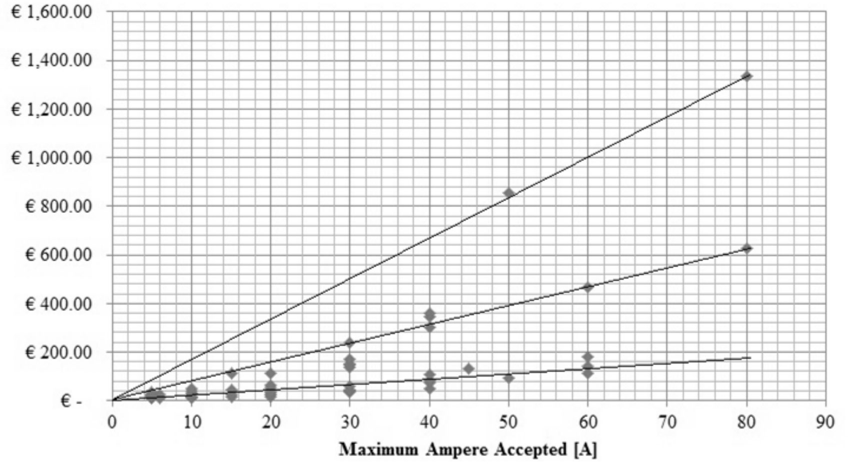


Fig 1.17 Price of Charge Controller resulting from author's elaboration after market survey.

The Internship period: from main problems to the decision support tool

The main purpose of the internship was to help Village Energy to find ways to make progress in efficiency and gain competitiveness. During the period spent in Uganda by the author, the reality of the company has been studied in depth to understand what were the issues on which it was possible to act in the short time available. In this direction, the first step has been to outline the main problems that put a strain on survival of the firm, which are:

1. An unfair competition: Village Energy products compete with imported products manufactured in East Asia that present extremely low prices. The quality is becoming a factor in the customer's choice only among people with high budget.
2. The low costumer's willingness and capability to pay: the average costumer comes to Village Energy's offices with a very low budget coupled with great expectations to provide a solution to their lack of energy. The problem is that people doesn't know how much does it cost a good PV panel and battery on the market. Thus, every day Village Energy has to do with clients that arrived convinced to buy a PV system for lighting their house, but when they realize that, with their budget, they can only light half of that, they become suspicious and leave the office saying "I'll call back". This situation may recur from 2 to 5 times a day (demonstrating a good interest in solar products) and is so frustrating for everyone in the company.
3. The financial difficulties: when Village Energy close a contract the payment is normally at the end of the installation, sometimes happens also that the client promises to pay the all amount, but when comes the day he realizes that he has only an half and the remaining part will come. The problem is that in such situation the company has to buy the all components anticipating money. This could be not a problem if the system to provide is one of the standardized products presenting low cost of goods, different is the case of a big customized system with a cost of goods of 4-8 Million UGX. Village Energy in most of the case doesn't have this amount available and is forced to contract debts without have the certainty of the client's payment after the installation. The reality is that the company's survival is linked to such these big installations to pay salaries and fixed costs.
4. The slowness in operating: the evaluation of the components necessary to set the systems is not easy, especially when the client's desiderata need to be satisfied with a customized system. Only Steven Muwanguzi, the chief-technician, has the

> sensibility to decide which size of PV panel, battery, charge controller and so on are required. However, when Steven is not in the office the others employees, with no technical skills and no instrument, which can help them, cannot take a decision and are forced to ask the client to come back later. This inefficient process implies the necessity of a long time to close an order. Sometimes months pass from the first contact with the client to the final quotation. Nevertheless, in most cases, the client doesn't come back and he looks for other companies.

The second step has been to focalize the attention and try to find a solution to one of these problems according with the technical knowledge of the author. Thus, the fourth problem was chosen as the only one that required a technical solution. The *VE Sizing&Pricing* tool (the functioning of which is deeply explained in Chap. 3) comes like a decision support tool to solve the fourth problem. Composed by simple Microsoft Excel sheets, has been designed by the author to size SAPV systems and make everyone in Village Energy capable of giving updated quotation in some minutes to the client after having ordered the information coming from him. To build it up, firstly the information from all the Village Energy's staff was collected in order to set up an upgradable database. Then the *Device sheet* has been thought to collect the customer's desiderata. After that, the *Sizing sheet* has been developed with the idea of putting all the expertise of the chief technician in a digital format. Finally, the *Pricing sheet* has been designed able to take the information from the database and help the employee to make a quotation for the client filling a final *Quotation sheet*.

Chapter 2

2. “Off-Main-Grid” Photovoltaic Systems: Sizing Methodologies and HOMER Software

The main objective of this chapter is to introduce the reader to “Off-Main-Grid” Photovoltaic systems and to focus and review the sizing methodologies developed in the scientific literature and in the most common software available. In the first section, the technology that characterizes these systems is exposed through an essential analysis of each component. Then, the main layouts are presented in order to identify the differences in applications. Finally the sizing methodologies are investigated. Specifically, two sizing methods available in the scientific literature, namely the intuitive and numerical method, and the commercial software *HOMER* are described in details, since they are implemented and applied in subsequent chapters.

2.1 “Off-Main-Grid” Photovoltaic technology

A PV system converts sunlight into electricity. It contains different components including cells, electrical connections, mechanical mounting and, if required, a way to store and convert the electrical output. Electrical conditioning equipment is also required to ensure the PV system to operate under optimum conditions.

“Off-Main-Grid” Photovoltaic systems, the typical layout of which is represented in Fig 2.1, are designed to operate independent of the electric grid, and are generally designed and sized to supply certain DC and/or AC electrical loads which can occur also during the night or hours of darkness. Thus the storage must be added to the system and generally batteries are used for this purpose. Several types of batteries can be used such as lead-acid, nickel–cadmium, lithium zinc bromide, zinc chloride, sodium sulfur, nickel-hydrogen, redox and vanadium batteries. Different factors are considered in the selection of batteries for PV application but, in most cases, lead-acid batteries are preferred due to more affordable costs that make them the only feasible solution in underdeveloped areas. When the system must provide AC power, an inverter, which uses an internal frequency generator to obtain the correct output frequency, is also required. Finally, in order to keep the battery at the highest possible state, while protecting it from overloaded by the photovoltaic generator and from over-discharge by

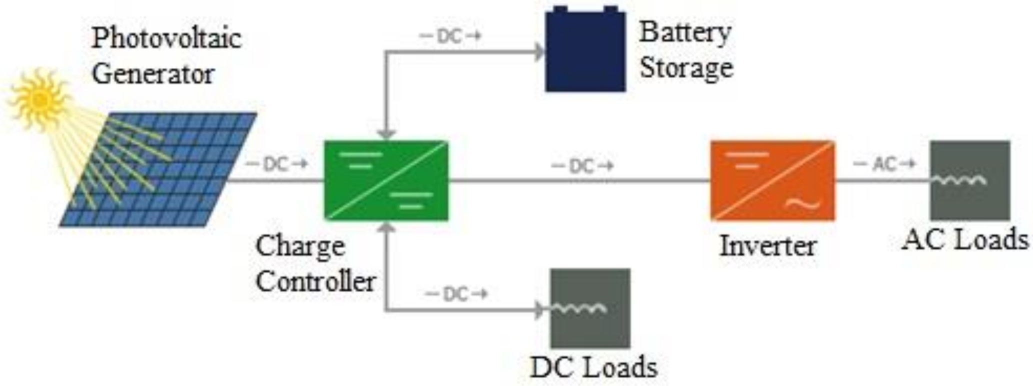


Fig 2.1 “Off-Main-Grid” system layout.

loads, a charge controller must be added to the system. In the next paragraphs, a brief overview of each component is presented to the reader with the intent to illustrate the key aspects that affect the sizing of an “Off-Main-Grid” Photovoltaic system.

Solar Radiation

Solar radiation consists of photons carrying energy E_{ph} that is given by the following equation:

$$E_{ph} = h\frac{c}{\lambda}$$

Where k is the wavelength, h Plank’s constant and c is the velocity of light. Global radiation comprises three components:

- Direct solar radiation: the sun radiation received directly from the sun.
- Diffuse radiation scattered by the atmosphere and clouds.
- Reflected radiation from the ground.

Since “Off-Main-Grid” photovoltaic systems use global radiation (which is the opportune combination of the three components of above) as energy resource, some definitions need to be specified since they recur in subsequent sections, in particular the distinction between irradiance and irradiation. Irradiance is an instantaneous quantity describing the flux of solar radiation incident on a surface (kW/m^2) [22]. The density of power radiation from the sun at the outer atmosphere is 1.373 kW/m^2, but only a peak density of 1 kW/m^2 is the final incident sunlight on earth’s surface. Irradiation measures solar radiation energy received on a given surface area in a given time, it is the time integral of irradiance given, for example, into kWh/m^2 per day. Insolation is another name for irradiation. Referring to a standard irradiance of 1000 W/m^2, insolation is usually given in hours, indeed in literature it is possible to find also insolation named as Peak Sun Hours. Fig 2.2 gives the relation between irradiance and insolation.

PV Generator

The basic element of a photovoltaic system (PV) is solar cells, which convert the sunlight energy directly to direct current. A typical solar cell consists of a P-N junction formed in a semi-conductor material similar to a diode. Semi-conductor material most widely used in solar cells is silicon. Nevertheless, there are several types of solar material cells and each material gives different efficiency and has different cost:

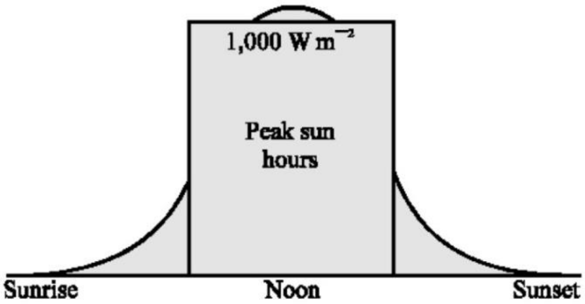


Fig 2.2 Irradiance and Peak-Sun-Hours relation [22].

- Monocrystalline Silicon cells: to make them, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. The cells have a uniform colour, usually blue or black. The highest efficiency of silicon solar cell is around 23%.
- Polycrystalline Silicon cells: in this case, the molten silicon is cast into ingots forming multiple crystals. These cells have slightly lower conversion efficiency compared to the single crystal cells but also lower costs due to the easier production process. To further reduce costs, ribbon silicon cells are polycrystalline cells made by growing a ribbon from the molten silicon instead of an ingot.
- Thin films: thin-film solar cell (TFSC) is a solar cell made by thin film materials with a few µm or less in thickness. Thin-film cells cost less than crystalline cells. Thin-film solar cells usually used are:
  1. Amorphous silicon (a-Si) and other thin-film silicon (TF-Si). The efficiency of amorphous solar cells is typically between % and 13%. Their lifetime is shorter than the lifetime of crystalline cells.
  2. Cadmium Telluride (CdTe), which is a crystalline compound formed from cadmium and tellurium and its efficiency is around 15%.
  3. Copper indium gallium selenide (CIS or CIGS) is composed of copper, indium, gallium and selenium. Its efficiency is around 16.5%.

In the photovoltaic module, that is the commercial PV unit, numerous cells are connected in series and parallel circuits in order to obtain high power. A PV panel consists of one or several modules grouped together on a common support. Finally, a number of solar panels can be combined in order to form a PV array with the desired output capacity. This fact gives to this technology a high degree of modularity making it suitable for a different range of applications.
The electrical characteristic of the PV cell is generally represented by the current versus voltage (I_{PV}-V_{PV}) curve showed in Fig 2.3 where I_{SC} and V_{OC} are respectively the short circuit current and the open circuit voltage. An important point of that characteristic is the maximum power point (*MMP*) which is located on the knee of the curve where the product between voltage and current is maximum. However, the power output of a PV cell is strongly affected by different variables:

- Levels of radiation;
- Cell’s temperature;
- Orientation and tilt angle;
- Shading and dust;
- De-rating of power during years.

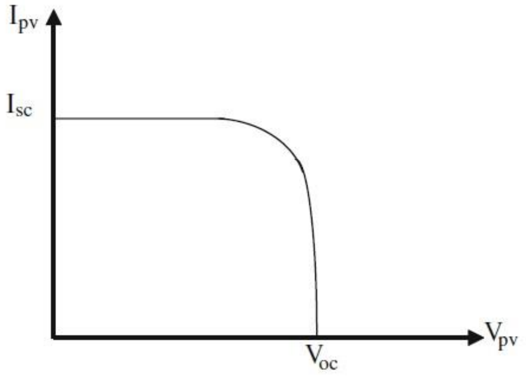


Fig 2.3 I-V characteristic of a Photovoltaic cell [22].

Fig 2.4 shows the current–voltage characteristics I_{PV}-V_{PV} and power–voltage P_{PV}-V_{PV} of the PV cell for different levels of radiation. It is possible to note that the current I_{sc} increases almost linearly with irradiance and that the voltage V_{oc} increases slightly. Since the characteristic of a PV cell is strongly dependent on test conditions, it is necessary to define a standard. The rated power of a cell is the power at the maximum power point of the I-V characteristic at an irradiance h of 1 kW/m^2, an ambient temperature of 25 °C and an air mass value of 1,5. In terms of energy, this means that a cell of rated power of 1W can produce 1 Wh only if a constant incident solar irradiance of 1 kW/m^2 shines on his surface for an hour. Otherwise, incident irradiation data are required in order to calculate the energy output. By relating them with the irradiance h of 1 kW/m^2 is possible to obtain the equivalent time-step in which the cell has worked under rated condition. The same applies also to the behaviour of PV cell under different light's spectrum, the standard spectrum commonly used is that one named AM 1.5 but in real condition, the light spectrum can be different, and that has also an effect on the PV power output.

Fig 2.5 shows that when the internal temperature T_j increases, the short circuit current I_{sc} increases slightly due to better absorption of light but the V_{oc} strongly decreases with temperature. The maximum electric power also strongly decreases with temperature. In order to take into account temperature effect, in literature equations that relate the internal temperature, which is usually named as cell temperature (T_{Cell}) to solar radiation, are available. Then, using datasheets of manufacturers that normally give the negative temperature coefficient of power ρ at the MPP respect to solar cell temperature, it is possible to rectify the power output of the cell.

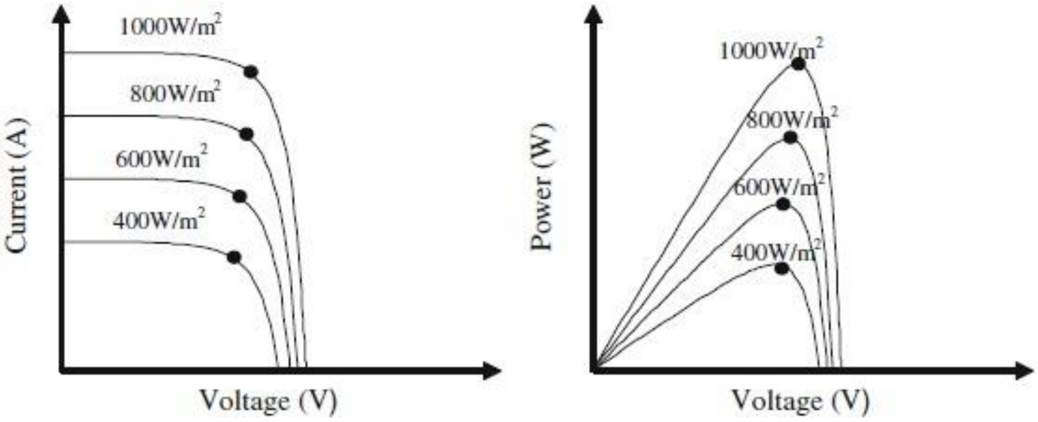


Fig 2.4 I-V and P-V characteristics of a photovoltaic cell for different level of irradiance [22].

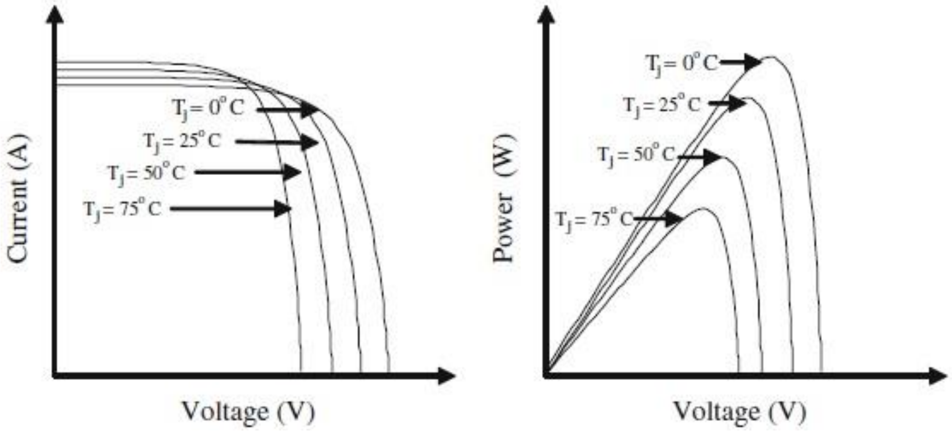


Fig 2.5 I-V and P-V characteristics of photovoltaic cell for different ambient temperature [22].

For maximum output, the face of the photovoltaic modules should be pointed as straight toward the sun as possible. The tilt angle (β) of the photovoltaic, which is the angle between the panel's surface and the horizontal, is the key to an optimum energy yield, indeed the cells' output increases when they are perpendicular to the sun's rays. Then, to maximize the collection of the daily and seasonal solar energy, PV modules should be oriented geographically. In the northern hemisphere the optimum orientation for a PV module is through south (Azimuth angle (γ) = 180°) while in the southern hemisphere trough north (Azimuth angle (γ) = 0°). Particular attention should be paid in case of installations located between the two tropics since the optimal orientation changes from north to south throughout the year, so it is advisable to leave the panels horizontal without tilt. To help the designer, come the tracking systems that mechanically move the panels in such a way that they are at the best inclination and azimuth during the day.

Moreover, avoid shading from surrounding obstructions and clean the panels frequently to remove dust or dirt that has accumulated, are precautions necessary because otherwise the surface area is reduced and, consequently, the power is negatively affected.

Finally, photovoltaic cells are affected by loss of power during the years of operation. Apart from catastrophic failures, modules generally degrade slowly due to degradation of silicon, solder joints or problems with the encapsulant (increased opacity, delaminating, water ingress). In a field test of 204 crystalline silicon PV modules it was found [23] that 70% of modules had an annual maximum power degradation rate lower than 0.75%, with only 35 out of 204 modules tested losing more than 20% of their rated power after 25 years. Based on this study and others [24] it seems reasonable to assume that module degradation will typically be in the range of 0.3–0.8% per year.

Lead-Acid Batteries

The battery storage is a fundamental component in an "Off-Main-Grid" PV system since permits to stock the energy in excess from the power source and make it available to the load when the same power source is not working. At the basis of the operation of each battery there is a reversible chemical reaction that, in the case of lead-acid batteries, is shown in Fig 2.6. The potential difference between electrodes is approximately 2.12 Volts when the cell is fully charged. As cells are connected in series, multiples of 2.12 Volts can be achieved. Most commonly, either three or six cells are connected in series, producing nominal voltages of 6 or 12 Volts.

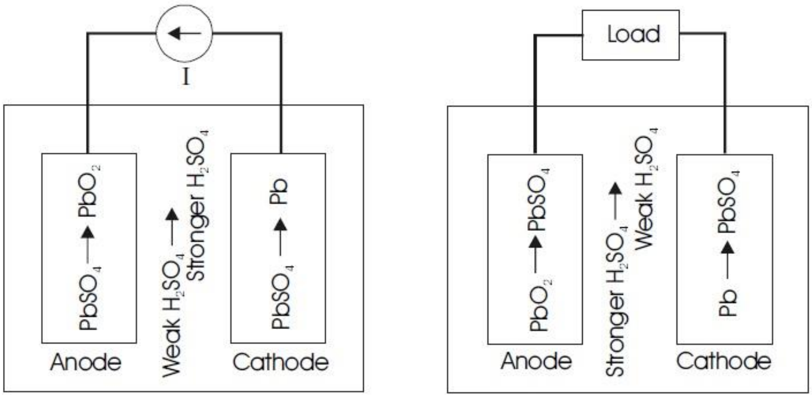


Fig 2.6 Charging and Discharging processes of a Lead-acid battery [25].

Ideally, the charging and discharging processes of the lead-acid system should be reversible. In reality, however, they are not. The temperature of operation, the rate of discharge and the rate of charge all affect the performance of the battery. Since the electrical path of the battery presents internal resistance, some of the electrical energy intended for charging is converted to heat. Typically, the charging process is about 95% efficient [25]. The discharge process also results in some losses due to internal resistance of the battery, so only about 95% of the stored energy can be recovered. The overall efficiency of charging and discharging a lead-acid battery is thus about 90%. Moreover, batteries are affected also by self-discharge process. This process happens when battery is not in use and the speed is highly variable and dependent on the type of battery and temperature. For example, a traditional lead-acid battery gets to lose 1% of charge on the day. The capacity of a battery is often referred to as *C*. Thus, if a load is connected to a battery such that the battery will discharge in *x* hours, the discharge rate is referred to as *Cx*. Note that higher discharge rates result in less charge being available as energy to the load. At higher charging rates, a smaller fraction of the charging energy is used for this scope because a larger fraction is used to heat up the battery.

For PV application deep discharge lead-acid batteries are used. These batteries use antimony to strengthen the lead and can be cycled down to 20% of their initial capacity. Although the deep discharge batteries are designed for deep discharge applications, it is worthwhile to underline that the lifetime in cycles of charge-discharge depends on the depth of discharge during normal operation as shown in Fig 2.7. Indeed the most common cause of death of a battery, together with the mechanical breaking is the sulphating of the plates, which occurs when the battery is discharged too in deep and too much lead sulphate is formed on the plates in the crystalline form, stopping completely the electrochemical activity in the battery. Under these conditions, the battery becomes unusable and cannot be recharged if not at a level much lower than its rated capacity. This is the reason why a lead battery should never be completely discharged, typical values of maximum depth of discharge are around the 60%. Moreover, these deep-cycle batteries produce significantly more hydrogen and oxygen gas from dissociation of water in the electrolyte, and thus, water must be added frequently to the battery to prevent the electrolyte level from falling below the top of the electrodes. Then, for applications where maintenance of batteries is inconvenient, sealed deep-cycle batteries exist, but are generally at least double the price of equivalent capacity non-sealed lead-acid units. These batteries are valve regulated to recombine gases, with additional treatment to immobilize the electrolyte.

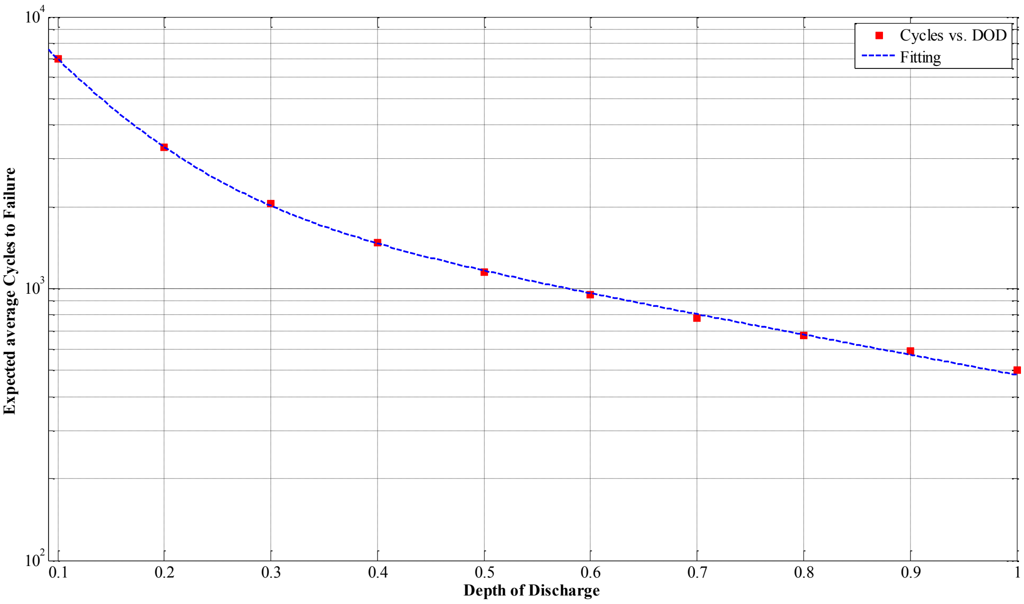


Fig 2.7 Depth of Discharge VS Expected average Cycles to Failure for a lead-acid battery.

Example of this category is *Gel Cells* which are sealed, lead-acid deep-cycle batteries that have silica gel added to the electrolyte. In addition to being maintenance free, sealed deep-discharge units have also a longer lifetime.

In this framework, different mathematical models have been developed to predict the performance of batteries. However, none of these models is completely accurate because the factors that affect battery performance are numerous:

- State of charge: the evolution of which depends from charge/discharge current;
- Battery storage capacity: which can vary according to the current imposed;
- Rate of charge/discharge: which affect the state of charge evolution;
- Environmental temperature: that impacts on the chemistry behaviour;
- Age effects: which impacts on the battery remaining capacity.

Charge controllers

In nearly all systems with battery storage, a charge controller is an essential component. All the charge controllers have the purpose to shut down the load when the battery reaches a prescribed state of discharge and to shut down the PV generator when the battery is fully charged. Using hysteresis loops as shown in Fig 2.8, the controller can prevent over-charge and over-discharge processes that can occur due to fluctuation in battery voltage that make difficult to decide a unique voltage to disconnect batteries in both sense.

Two products are competing on the market, differentiating themselves by the different ability to exploit the energy from the PV generator for charging batteries: Pulse Width Modulator technology (PWM) and Maximum Power Point Tracking technology (MPPT). The PWM charge controllers represent the cheaper technology. The attention is focus on the voltage required to charge the battery. If the voltage of the PV generator resulting from a particular insolation is higher than the voltage required by the battery, the pulse width modulation start to work making sure that the resulting

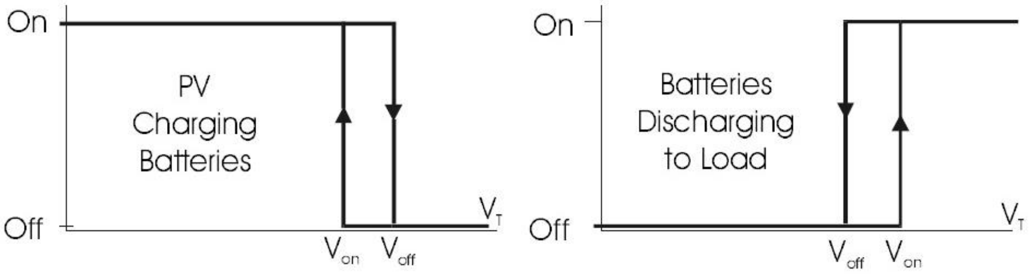


Fig 2.8 Hysteresis loops in charge controllers’ operation [25].

voltage across the battery has been actually to that required. The drawback lies in the fact that the regulator rejects the power of the PV in proportion equal to the differences between the PV generator voltage and the voltage required by the battery. To solve these problems is spreading the MPPT technology that shifts the focus on the total power from the photovoltaic generator, having the purpose of enabling the photovoltaic generator to work in the maximum power point. Thus, if a case like the one presented before, occurs in a system with an MPPT charge controller installed, the controller then proceeds by reducing the voltage to that required from the battery, but at the same time raising the current in order to keep the maximum total power from the generator. The negative point in this case are clearly the higher costs that make the technology completely out of sense when compared to the cost of the small systems normally sold in underdeveloped contexts.

Inverter

An inverter is a device that converts direct current to alternate current and is one of the key elements in an “Off-Main-Grid” photovoltaic system designed for AC loads. In the case of an inverter system, the amount of DC power required to supply an AC load is determined by the efficiency of the inverter. Normally an inverter is sized on the maximum load required by the user with a precautionary oversizing factor that takes into account unpredictable fluctuations of the load.

2.2 “Off-Main-Grid” Photovoltaic layouts

“Off-Main-Grid” Photovoltaic Systems can be classified into two categories [10]:

1. Stand-Alone Photovoltaic (SAPV) systems: which are systems the purpose of which is to meet the needs of an individual customer, be it a person, a household or a business activity. According to the size it is possible to distinguish:
   - Pico Solar Systems;
   - Solar Home Systems (SHS);
   - Community Based Systems.
2. PV Micro-Grid: which are centralized systems that can supply, through a common distribution network, the needs of a number of households and community services.

Pico Solar Systems (Fig 2.9) are defined as small solar systems, normally portables, with a power output of 1–10 W, mainly used for lighting, and thus able to replace sources such as kerosene lamps and candles. Devices are powered by a small solar panel and use a battery, which can be integrated in the device itself.

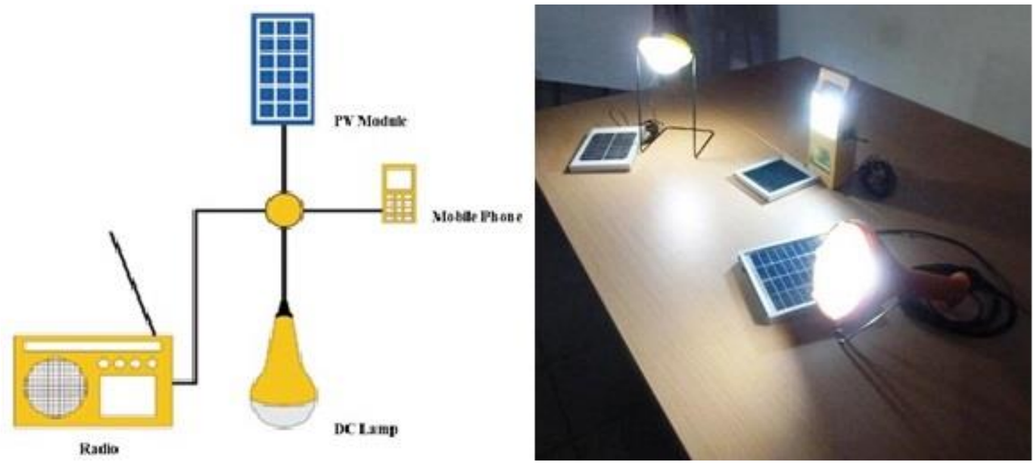


Fig 2.9 SAPV - Pico Solar System layout [10] and commercial Pico Solar Systems Products [26].

Solar Home Systems consist of a PV module, a charge regulator, lead-acid deep-cycle battery, and optionally an inverter. Generally, these systems cover a power output of up to some hundred Watts. The configuration without an inverter (Fig 2.10-A) makes solar home systems very energy efficient. In this case, the charge controller is the core of home-based systems, since it ensures optimal charging and discharging and avoids damages. However, when DC loads are not available an inverter is required and the configuration of the system change to the one exposed in Fig 2.10-B.

Community Based Systems are larger Stand-Alone PV systems that provide energy to community services such as health centres, schools and factories. In this case, generally an inverter is needed (Fig 2.11). With a typical range from some hundred to some thousand Watts output power, community systems usually integrate 12 or 24 Volts batteries, even if bigger systems work with higher voltage.

Finally, PV Micro-Grids can provide electricity to a number of households and community services. In this case, solar panels arrays are assembled in the range of some hundreds of kW, and a distribution network provides the electricity to the connected loads.

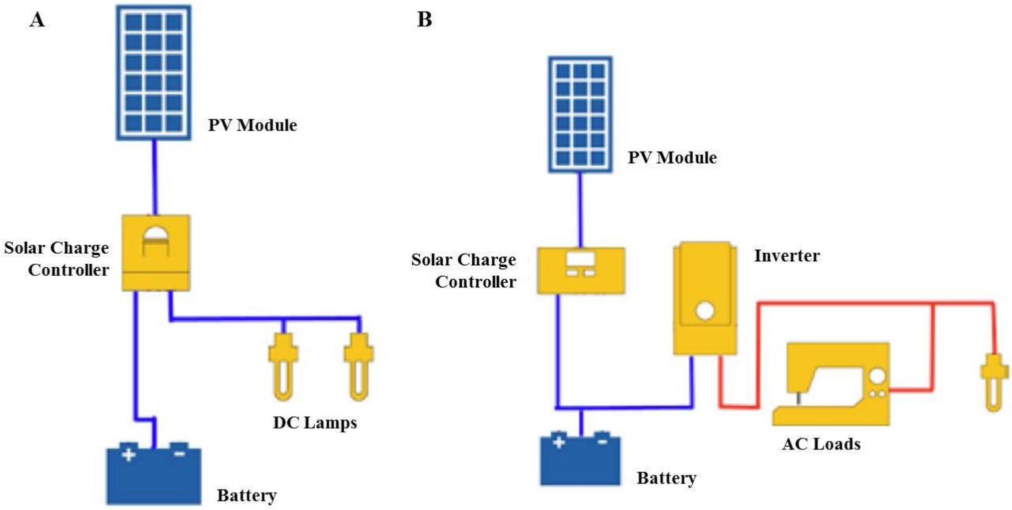


Fig 2.10 SAPV-Solar Home Systems. Layouts for DC loads (A) and AC loads (B) [10].

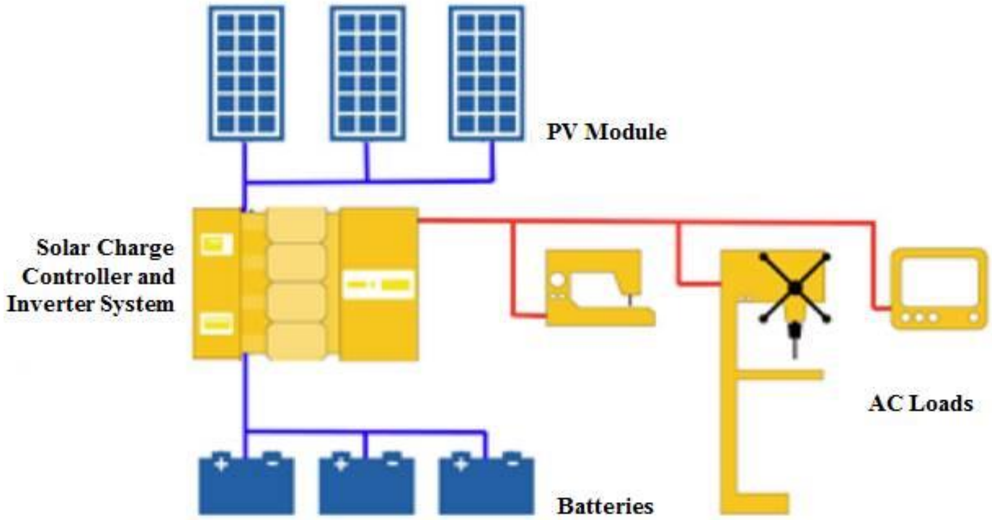


Fig 2.11 SAPV - Community Based System layout [10].

The complexity of the system is higher. Essential elements of the systems are:

- PV array.
- Battery banks for electricity storage.
- Power conditioning unit (PCU) consisting of junction boxes, charge controllers, inverters, distribution boards and necessary wiring/cabling.
- Power distribution network (PDN) consisting of conductors, insulators, wiring/cabling.

PV Micro-Grids can give the possibility to electrify rural or peri-urban areas with a centralized solution. Assuming for example a village composed by 100 households, the same results in terms of electrification can be obtain with 100 SHS installed on each roof or with a unique centralized photovoltaic Micro-Grid connected to each user. The benefits of the second solution are in terms of reliability and total costs being able to take advantage of economies of scale.

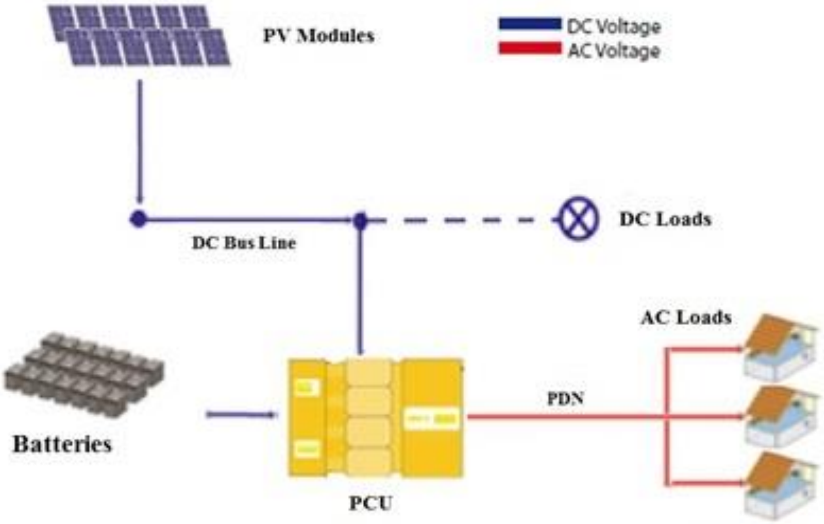


Fig 2.12 PV Micro-Grid layout. Author’s elaboration based on [10].

2.3 Sizing methodologies

Within the scientific literature there are three sizing procedures for “Off-Main-Grid” systems [23]. Each of them requires data about the load and the resource. These input data may vary in terms of temporal detail and accuracy in measurement or estimation. Moreover, behind each sizing method there are assumptions about the particular modelling of system components. The degree of details in system components modelling varies depending on the accuracy of the results to be obtained and the purpose of the analysis. In any case and apart from specific analyses carried out, given these assumptions, the sizing methods always provide quantitative results in terms of size of panels and batteries and (often) cost of the system. The above-mentioned sizing procedures are:

1. The Intuitive methods ([27] - [34]): which are defined as a simplified calculation of the size of the system carried out without establishing any relationship between the different subsystem or taking into account the random nature of solar radiation and loads. They are mostly chosen for their simplicity in calculations, which makes them more intelligible and replicable by non-expert designer. The negative point of this approach is the results’ approximation which can lead to an over or an under sizing problem.
2. The numerical methods ([35] - [49]): in which different systems, (i.e. different combinations of panels and batteries), are simulated on yearly basis and a common criterion is used to choose the best combination that addresses the load. For each time period considered, usually an hour, the energy balance of the system and the change in the battery load state of charge is calculated. Generally, they are preferred when more accurate results are required in order to optimize the energy and economic cost of the system. Numerical methods have also the advantage of allowing additional aspects of sizing to be analysed such as the different models for the systems components. The drawbacks of these systems are the long calculation time required and the need of long and accurate data sequences.
3. The analytical methods ([50] - [59]): in which functional relationships between the variables of interest lead to solve the sizing problem (i.e. usually developed as a mathematical optimization problem with an objective function subjected to one or more conditions). One of the main shortcomings of these methods is that either they are not accurate enough or they require the determination of specific coefficients for the functional relationship. On the other side, their strongest advantage is that the simulation of the different subsystem sizes is simple and relatively fast.

As results of the above procedures, on the market there are already available a lot of software that implement these different methodologies giving automatically the required results after having asked required inputs from the user. They can be reassumed in two main categories.

1. PV system-performance programs: which mostly use intuitive methodology to give the performance information of a PV system. The best known are:
   - PVGIS by European Commission [60]: which is a Web application to estimate the performance of PV systems located in Europe or Africa.
   - RETScreen by CANMET [61]: which is a renewable energy decision support and a capacity building tool. Each RETScreen renewable-energy-technology model, including “Off-Main-Grid” PV system, is developed within and individual Microsoft Excel spreadsheet workbook file.

   - NSOL by Fear The Skunk [62]: which includes modules for “Off-Main-Grid” PV.
2. PV system simulation softwares: the architecture of which is substantially based on numerical or analytical methods. The best known are:
   - *HOMER* by NREL [63]: which is a computer model that simulates and optimises Stand-Alone electric hybrid power systems. It can consider any combination of renewable technology included PV system. The design optimization model determines the configuration that minimises life-cycle costs for a particular site application.
   - TRNSYS by Solar Energy Lab [64]: this tool was first created to study passive solar heating systems. Nowadays has been revised and includes main components systems including solar PV panels and batteries.
   - PV*SOL Expert by Valentin Energy Software [65]: which is a program for design, planning and simulation of a PV systems. Program features include “Off-Main-Grid” systems.

Intuitive and numerical methods have been selected for further investigation and they are deeply described in the next sections. Indeed, they are at the basis for the applications that are shown in Chap. 3 and Chap. 4.

For each methods, firstly the main and basic structure is exposed with the help of a schematic flow-chart, then, the principal modifications to the basic structure that are investigated the most in literature are detailed. In addition, a brief but comprehensive overview of the software *HOMER* is presented since it has been found to be most widely used tool for analysis of “Off-Main-Grid” systems for rural electrification and because it has been used to compare results obtained in the application of the intuitive and numerical methods.

2.3.1 Intuitive methods

The intuitive method is defined as a simplified calculation of the size of the PV system carried out without establishing any relationship between the different subsystems or taking into account the random nature of solar radiation and loads. Starting from monthly averaged insolation and with no regards to the complexity of the single component, it is quite easy to size the solar home system receiving as outputs the power of panels and capacity of batteries that responds to the customer’s needs.

To calculate the PV array size the Energy balance between load and system’s output needs to be formulated. Indeed, Equation (2.1) represents the overall balance for the average day of the month m in which the output from the photovoltaic system ($E_{PV,m}$) equals the energy required by the load (E_L) passing through the inverter efficiency, the battery efficiency (which explains the charge and discharge performances of the batteries) and balance of system efficiency (which takes into account the other losses not related directly to the sun energy conversion process).

$$E_{PV,m} = \frac{H_m\, P_m}{h}\, \eta_{BOS}\, \eta_{Inv}\, \eta_{Bat} = E_L \tag{2.1}$$

Where, H_m is the specific mean daily solar irradiation on horizontal surface values of the chosen month (kWh/m^{2}day) and P_m is the rated power from photovoltaic generator installed (kW) at an irradiance h of 1 kW/m^2, an ambient temperature of 25 °C and an air mass value of 1,5. Mean daily solar radiation values for every month and other useful data can be found on the website of the NASA atmospheric science data center

[66]. Note that the rated power accounts for both the area and the efficiency of the PV installed, so neither of those parameters appears explicitly in the next steps. Solving the equation, we can obtain the PV power that needs to be installed for each month of the year.

$$P_m = \frac{E_L\, h}{H_m\, \eta_{BOS}\, \eta_{Inv}\, \eta_{Bat}} \tag{2.2}$$

Then, two approaches can be followed. The first one is to set the power of the photovoltaic system (P_{PV}) on the average value of monthly solar irradiation, the second one on the maximum value of them with a conservative choice.

Concerning the storage, to size the battery bank the simplest approach is to have a battery bank capable to give the energy required by the load during the night ($E_{L,\ night}$):

$$E_{Bat} = \frac{E_{L,night}}{(1 - SOC_{min})\ \eta_{Inv}\, \eta_{Bat}} \tag{2.3}$$

Where SOC is the State Of Charge of the battery, thus SOC_{min} is the percentage of energy that wants to remain at minimum to preserve the life of the battery. In other words, $(1\text{-}SOC_{min})$ is the permissible Depth Of Discharge (DOD_{max}) of the battery. Another and more conservative approach is to size the battery system in order to satisfy a selected number of no-sun days [32]. In this case, instead of $E_{L,night}$ in Equation (2.3) a multiple of the daily load is required as follows:

$$E_{CD} = n_{CD}\, E_L \tag{2.4}$$

Where n_{CD} is the number of cloudy days which may be a given project data, resulting from the needs of the customer, or may be found on the website mentioned above.

Equations (2.1-4) have been showed the basic structure of the intuitive sizing method, which is graphically explained in Fig 2.13.

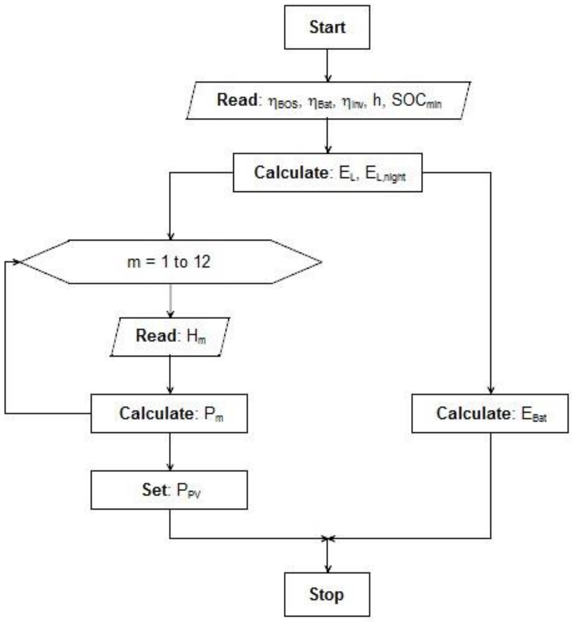
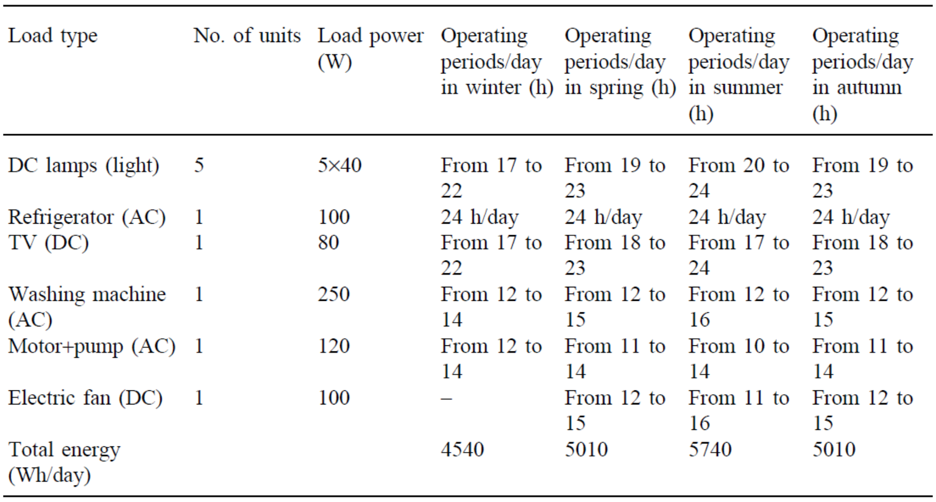


Fig 2.13 Flow-chart of the intuitive method.

Table 2.1 Estimation of the energy demand for a typical family house [31].



Load type	No. of units	Load power (W)	Operating periods/day in winter (h)	Operating periods/day in spring (h)	Operating periods/day in summer (h)	Operating periods/day in autumn (h)
DC lamps (light)	5	5×40	From 17 to 22	From 19 to 23	From 20 to 24	From 19 to 23
Refrigerator (AC)	1	100	24 h/day	24 h/day	24 h/day	24 h/day
TV (DC)	1	80	From 17 to 22	From 18 to 23	From 17 to 24	From 18 to 23
Washing machine (AC)	1	250	From 12 to 14	From 12 to 15	From 12 to 16	From 12 to 15
Motor+pump (AC)	1	120	From 12 to 14	From 11 to 14	From 10 to 14	From 11 to 14
Electric fan (DC)	1	100	–	From 12 to 15	From 11 to 16	From 12 to 15
Total energy (Wh/day)			4540	5010	5740	5010

Load estimation

Load’s amount is one of the aspects that can be better modelled within an intuitive method. Literature shows that it is possible to define the energy demand reporting the consumption of each device under consideration as follows [32]:

$$E_L = \sum_{i=1}^{n} n_i V_i I_i h_i \qquad (2.5)$$

Where, n_i is the number of same *ith* device, V_i and I_i are voltage and current required by the loads and from which result the power consumption of the *ith* device. Finally h_i is the number of utilization hours of the *ith* device. It may be useful to divide the calculation according with different seasons (Table 2.1) and, based on the different hourly usage of the same device *ith*, it is possible to get different values for different months to put in Equation (2.2).

Tilt angle

The panel's tilt angle (β) changes the value of irradiation that affects the panel’s surface in Equation (2.1), correction factors or values of specific mean daily solar irradiation for different tilt angles (H_β) can be used to replace those on horizontal surface. A good rule to choose the tilt angle is to identify it with the latitude of the place of the photovoltaic installation. In temperate zones, if it’s possible to change the inclination, it’s better to pass from a tilt angle equal to the latitude minus 15° during the summer season, to an angle equal to the latitude plus 15° during the winter, when the sun is low on the horizon. In equatorial areas it is advisable to leave the panel horizontal, with no inclination.

Operating temperature

The operating temperature acting on the system affects both the panels than the batteries. Indeed, from the I-V characteristic of a photovoltaic module, as mentioned in the previous paragraph is evident that the voltage (V_{Mod}) is strongly affected by temperature. Some authors [28] find a way to solve the question getting the maximum ambient temperature, generally occurring during the hottest months, and adding an arbitrary ΔT to describe the module’s temperature under radiation. Then, re-entering in the I-V characteristics, it is possible to read the module working voltage at that temperature. The same authors take into consideration also the effect of the operating temperature on the batteries introducing a correction factor in Equation (2.3); in fact, variations in temperature can affect the chemical reactions inside the battery's cells.

Array sizing

Equation (2.1) and Equation (2.2) are not sufficient to obtain the number of panels and batteries that need to be installed on the site to address the customer's needs. The specifications of the components available for installation need to be considered. Thus, the number of modules necessary is:

$$n°_{Mod} = \frac{P_{PV}}{P_{mod}} \tag{2.6}$$

With, P_{Mod} the nominal power of each single module installed. The next step is to divide the modules in strings each of which must generate the desired voltage of the system (V_{Sys}). The number of modules for each string is given by:

$$n°_{Mod,st} = \frac{V_{Sys}}{V_{Mod}} \tag{2.7}$$

Where V_{Mod} is the rated voltage at the operating temperature. Then, the number of panel's strings is given by:

$$n°_{PV,st} = \frac{n°_{Mod}}{n°_{Mod,st}} \tag{2.8}$$

Obviously, each calculation has to be rounded up to the next entire number. Accordingly, the total number of modules and the total power that need to be installed is given by:

$$n°_{mod,TOT} = n°_{Mod,st} \cdot n°_{PV,st} \tag{2.9}$$

$$P_{Inst} = n°_{Mod,TOT} \cdot P_{mod} \tag{2.10}$$

Similarly, moving attention on the battery bank, the number of batteries necessary is:

$$n°_{BAT} = \frac{E_{Bat}}{E_b} \tag{2.11}$$

Where E_b is the rated energy available in each of the single battery installed. The number of batteries in series for each string, necessary to reach the system voltage, is given by:

$$n°_{Bat,st} = \frac{V_{Sys}}{V_{Bat}} \tag{2.12}$$

Where V_{Bat} is the nominal voltage of the selected battery resulting from the sum of each single cell voltage of which the battery is made. Then, the number of battery's strings is given by:

$$n°_{Bat,st} = \frac{n°_{Bat}}{n°_{Bat,st}} \tag{2.13}$$

Then, the total number of batteries required and the total energy that needs to be installed can be determined as following:

$$n^{\circ}_{Bat,TOT} = n^{\circ}_{Bat,st} \cdot n^{\circ}_{st} \tag{2.14}$$

$$E_{Inst} = n^{\circ}_{Bat,TOT} \cdot E_b \tag{2.15}$$

Economic estimation

From the economical viewpoint, “Off-Main-Grid” Photovoltaic systems are characterized by an high initial investment and low operating costs [31]. The costs that need to be considered include:

- The cost of PV modules: normally given as a specific cost per power c_{PV} (€/kW);
- The cost of storage batteries: normally given as a specific cost per capacity c_{Bat} (€/Ah, convertible in €/kWh passing through the nominal voltage of the battery);
- Inverter and controller’s cost: normally given as a specific cost per peak of power required c_{Inv} (€/kW);
- Other costs C_{Others}: comprehensive of design, installation and other stuff.

The life cycle (LC) is generally considered of 20 years, except for the battery, the duration of which can be precisely calculated or considered from 2 to 5 years according to the quality, and for the inverter and controller for which it is good thing considering a replacement in the middle of the life cycle of the system.

Having the assumptions is possible to calculate the cost of the investment (C_I):

$$C_{Inv} = P_{PV}c_{PV} + E_{Bat}c_{Bat} + E_{L,max}c_{Inv} + C_{Others} \tag{2.16}$$

As mentioned, other negative cash flows (CF) will occur in the next years principally due to operation and maintenance costs ($C_{O\&M}$) and the various components’ replacement of what above. Actualizing all these costs assuming a real interest rate r is possible to obtain the Net Present Cost of the system on its lifetime as following:

$$NPC = C_{Inv} + \sum_{i=1}^{LC} \frac{CF_i}{(1+r)^i} \tag{2.17}$$

Finally, to understand the cost of each kWh produced by the system is useful to divide the NPC on the total actualized energy produced during all over the life cycle time.

$$COE = \frac{NPC}{\sum_{i=1}^{LC} \frac{E_{PV}}{(1+r)^i}} \tag{2.18}$$

This parameter can be used to compare the “Off-Main-Grid” photovoltaic technology with other power technologies.

2.3.2 Numerical methods

The majority of the works in literature is based on numerical methods in which different systems (i.e. different combinations of panels and batteries) are simulated on yearly basis and a common criterion is used to choose the best combination that addresses the load. For each time period considered, usually an hour, the energy balance of the system and the change in the Battery SOC is calculated.

In this case, for both the solar resource and the load, the time series data of the year or day are required. The time step of the series can vary from hour to minute depending on the detail required and the presence of components' models that can exploit thicker time step. The optimization method considers three steps:

The first step involves estimation of PV energy output of the system under consideration for each time-step of simulation (t):

$$E_{PV}(t) = P_{PV} \frac{\mathrm{H}_{\beta}(t)}{h} \eta_{BOS} \tag{2.19}$$

Where, $H_{\beta}(t)$ is the specific solar irradiation on tilted surface value for the chosen time-step, P_{PV} is the rated power (kW) of the panels under simulation at an irradiance h of 1 kW/m^2, an ambient temperature of 25 °C and an air mass value of 1,5.

The second step is estimating the amount of energy that flows through the battery and the change in the battery state of charge. For each time-step the difference between PV array output ($E_{PV}(t)$) and load required by the user ($E_L(t)$) after inverter efficiency (in the case of an AC system) is calculated:

$$\Delta E = E_{PV}(t) - \frac{E_L(t)}{\eta_{Inv}} \tag{2.20}$$

Clearly, if the difference is positive the battery will be under charge, on the contrary a discharge will occur. In both cases the energy stored in the battery (i.e. the battery state of charge) needs to be updated based on the amount previously stored ($E_{Bat}(t-1)$).

$$E_{Bat}(t) = \begin{cases} E_{Bat}(t-1) + \Delta E\, \eta_{Bat,CH} \ , & \Delta E > 0 \\ E_{Bat}(t-1) + \dfrac{\Delta E}{\eta_{Bat,DISCH}} \ , & \Delta E < 0 \end{cases} \tag{2.21}$$

Where $\eta_{Bat,CH}$ and $\eta_{Bat,DISCH}$ are respectively the battery charge and discharge efficiencies. The self-discharge rate is normally not considered because the photovoltaic generator is the only source of power and batteries are always operative. Furthermore, the energy stored in the battery is subjected to the following constraints:

$$E_{Bat,min} < E_{Bat}(n) < E_{Bat,max} \tag{2.22}$$

$E_{Bat,max}$ is the maximum allowable energy level which is normally equal to the rated energy of the battery $E_{Bat,rated}$ (kWh):

$$E_{Bat,max} = E_{Bat,rated} = C_{Bat,rated}\, V_{Bat,rated} \tag{2.23}$$

Where $C_{Bat,rated}$ and $V_{Bat,rated}$ are respectively the nominal capacity (Ah) and the rated voltage (V) of the battery under consideration. $E_{Bat\ min}$ is the minimum allowable energy level, which must remain in the battery after a discharging period to have the battery life as stated in the battery specifications. It is determined by the maximum depth of discharge (DOD_{max}) or minimum SOC.

$$E_{Bat,min} = E_{Bat,rated}\, SOC_{\min} \tag{2.24}$$

In parallel with Equation (2.21) is possible to count the available energy in the battery as evolution of the state of charge:

$$SOC(t) = \frac{E_{Bat}(t)}{E_{Bat,rated}} \tag{2.25}$$

Thus, the charge controller, which is the component that monitors the battery *SOC* as an indicator of the battery status and the system status as well, is described in numerical models. In fact, when the *SOC* has reached the allowable minimum value the discharging process is stopped to protect the battery from over-discharging. When the *SOC* is 1 (fully charged), the charging process is stopped to prevent the battery from overcharging.

The battery model described above is the simplest battery model that can be implemented within numerical methods and literature refers to it as ideal battery model. It does not take into account the real behaviour of the battery, a very complicated component to describe, the performances of which are strongly related to the imposed workload.

The third and final step is to clarify an indicator to choose the optimum. In most of the cases, the loss of load probability (*LLP*) is adopted to describe the reliability of power supply to load [48]. Its definition is the percentage of the total load required by the user that remains not satisfied. An *LLP* of 0 means that the power can fully meet load demand; whereas an *LLP* of 1 means that the power can never meet load demand. An *LLP* from 0 to 1 means the power cannot fully supply to the load when the solar power is not enough while the battery has been under the minimum SOC.

In terms of the allowable minimum battery SOC, the *LLP* within a period of N time-steps can be mathematically computed as:

$$LLP = \frac{\sum_{t=1}^{N} \mathrm{LL}(t)}{E_L(t)} \tag{2.26}$$

Where *LL(t)* is the loss of energy supply at the selected time-step, which can be expressed as:

$$\mathrm{LL}(t) = \begin{cases} \dfrac{E_L(t)}{\eta_{Inv}} - \left(E_{PV}(t) + E_{Bat}(t-1) - E_{Bat,min}\right) \;, & SOC(t) < SOC_{min} \\ 0 \;, & SOC(t) \geq SOC_{min} \end{cases} \tag{2.27}$$

The purpose of the size optimization of solar array and battery is to match the load demand under an imposed LLP_{max} with the respect of the allowable minimum battery SOC at the minimum Net Present Cost over the life cycle of the system [48]. It is found that different size combinations of solar array and battery can meet the given load demand for the desired LLP. To determine the optimal size combination, the cost function of the “Off-Main-Grid” photovoltaic system is the Net Present Cost (NPC), as defined in Section 2.3.1 and summarized in the next equation:

$$NPC = P_{PV}c_{PV} + E_{Bat,rated}c_{Bat} + E_{L,max}c_{Inv} + C_{Others} + \sum_{i=1}^{LC} \frac{CF_i}{(1+r)^i} \tag{2.28}$$

Given the typical numerical sizing methodology, of which procedure is graphically explained in Fig 2.14, it is important to note that the discriminant to obtain more precise results in numerical methods is to have accurate models that best describe each component. This is especially true for batteries, the behaviour of which is very difficult to define in terms of both predicted lifetime and in terms of evolution of the state of charge during operation. The next few paragraphs are intended to present to the reader, models that try to better describe the real behaviour of photovoltaic modules and battery bank.

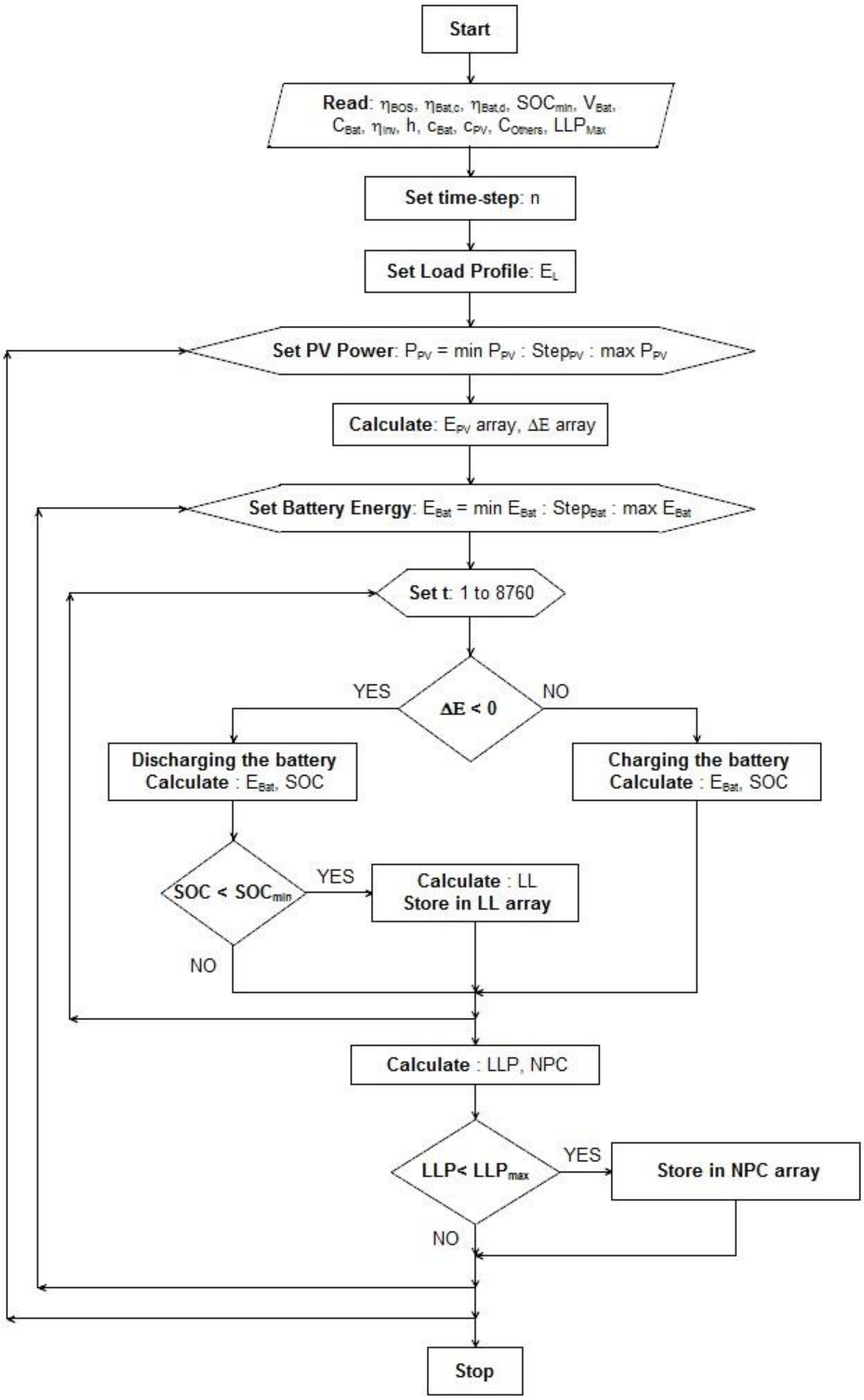


Fig 2.14 Flow chart of the numerical method on an hourly basis.

PV model: effect of operating temperature

The relationship between solar cell temperature and ambient temperature is established to consider temperature effect. The solar cell temperature at each time-step of the simulation can be calculated by using average ambient temperature (T_{Amb}) and average irradiance over the surface (G [kW/m^2]) occurring during the same time-step [49]:

$$T_{Cell}(t) = T_{Amb}(t) + \left(\frac{NOCT - 20}{0.8}\right) G(t) \tag{2.29}$$

Where *NOCT* is the Nominal Operation Cell Temperature (typically 44÷47 °C). As a result the PV energy output of Equation (2.19) can be corrected as follows:

$$E_{PV}(t) = P_{PV}\ (1 - \rho_T (T_{Cell}(t) - 25))\frac{\mathrm{H}_\beta(t)}{h}\ \eta_{BOS} \tag{2.30}$$

With ρ the negative temperature coefficient of power respect to solar cell temperature provided by the manufacturer (normally 0.35÷0.45 %/°C).

Battery model: State of Charge determination, Peukert equation

A battery cell is characterized by its capacity, an amount of current stocked into the battery. As known, this capacity is not fixed but depends on different factors among which the most important is the current intensity. In literature a lot of models has been developed trying to describe the real behaviour of batteries [22]. The simplest models are based on electrochemistry. These models can predict energy storage but they are neither able to model phenomena such as the time rate of change of voltage under load nor do they include temperature and age effects.

Among this category, the Peukert equation is an empirical formula that relates the capacity at one discharging rate to the capacity at another discharging rate.

$$C_1 = C_2\left(\frac{I_2}{I_1}\right)^{p-1} \tag{2.31}$$

Where *p* is the Peukert constant, directly related to the internal resistance of the battery, which varies according to the different battery types.

Starting from the rated capacity $C_{Bat,rated}$ and a constant testing parameter *C*20 it is possible to deduct the nominal current of the battery as follows:

$$I_{rated} = \frac{C_{Bat,rated}}{20} \tag{2.32}$$

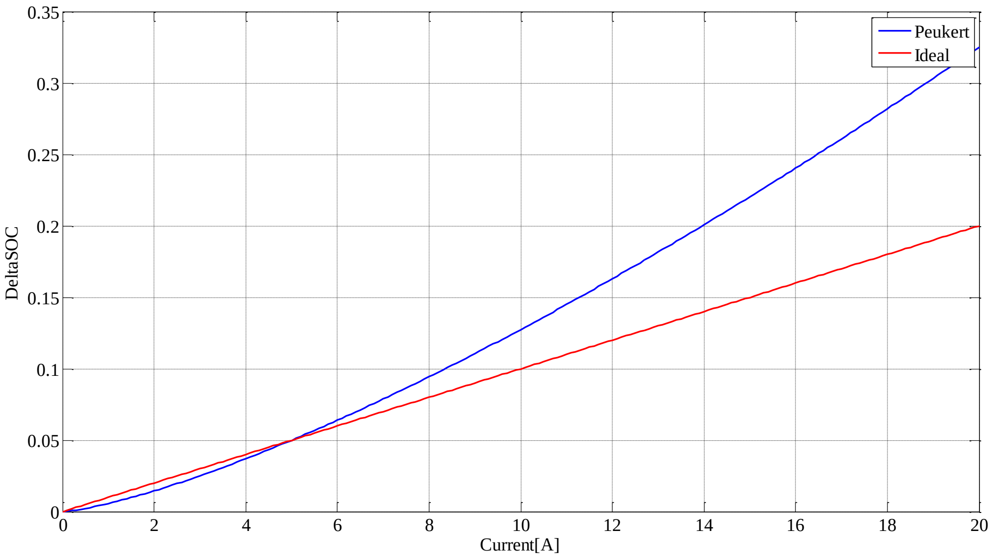


Fig 2.15 Variations in the state of charge using ideal and Peukert model for an overall lead-acid battery of 12V, 1.2 kWh C20.

Note that I_{rated} is the current which brings the battery to a fully discharge in 20 hours. Using the Peukert equation permits to derive the battery SOC after a charging or discharging time-step Δt by relating the current rate I_k with the nominal rate as in the next Equation.

$$SOC(t+1) = SOC(t) \pm \frac{I(t)}{C_{Bat,rated}} \left(\frac{I(t)}{I_{rated}}\right)^{p-1} \Delta t \tag{2.33}$$

The above Equation (2.33) is intended to replace Equation (2.25) in the general numeric method. It can be noticed that if $p=1$, the ideal model of battery is described also by Peukert equation. The Fig 2.15 shows the variations in the state of charge after 1 hour at a selected current, comparing the ideal (p=1) and the Peukert model of a lead-acid battery (p=1.35) for a battery whit a nominal capacity of 1.2 kWh at 12 Volts and a consequent nominal current of 5 A at C20.

The two models coincide only at the nominal current which, in agreement with the assumptions made before, it is the current that leads the battery to a 1/20 of charge or discharge. Moving from that point things substantially change. To better understand is useful to rewrite Equation (2.33) to explicit the variation of energy inside the battery in the selected time-step *k*.

$$\Delta E_{Bat}(t) = I(t) \left(\frac{I(t)}{I_{rated}}\right)^{p-1} \Delta t \, V_{Bat,rated} \tag{2.34}$$

Then, grouping some terms in Equation (2.34) it is possible to isolate the energy required by the load or given from the power source.

$$\frac{\Delta E_{Bat}(t)}{\Delta E_L(t)} = \left(\frac{I(t)}{I_{rated}}\right)^{p-1} \tag{2.35}$$

Looking at Fig 2.16 is clear that, according to Peukert equation, a kWh requested or sent to the battery has a different impact on the effective energy moved or removed in the battery, depending on how much the current rate is distant from the nominal value.

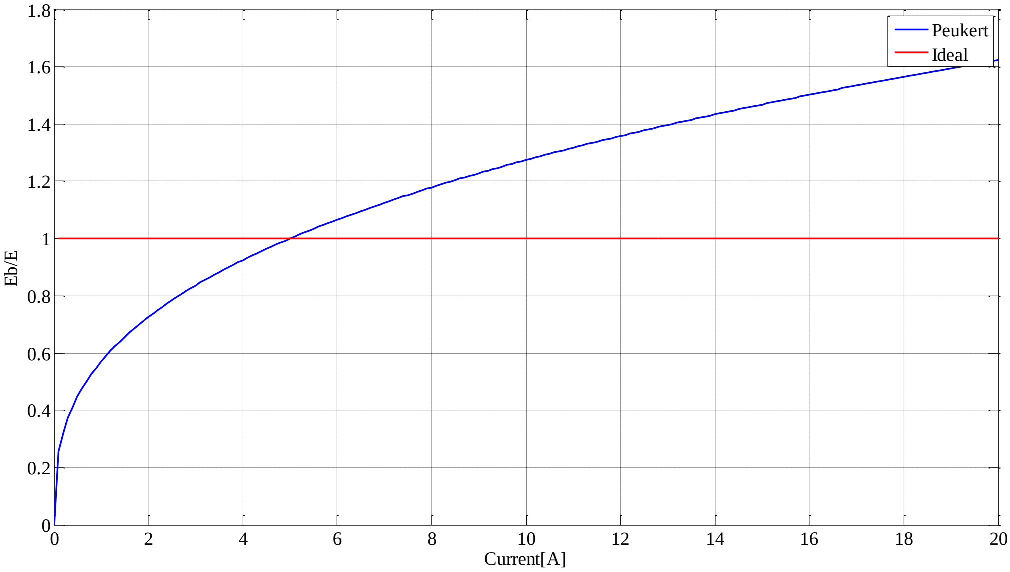


Fig 2.16 Relationship between the energy required or given to the battery and the effective variation of energy in the battery for a lead-acid battery of 12V, 1.2 kWh C20.

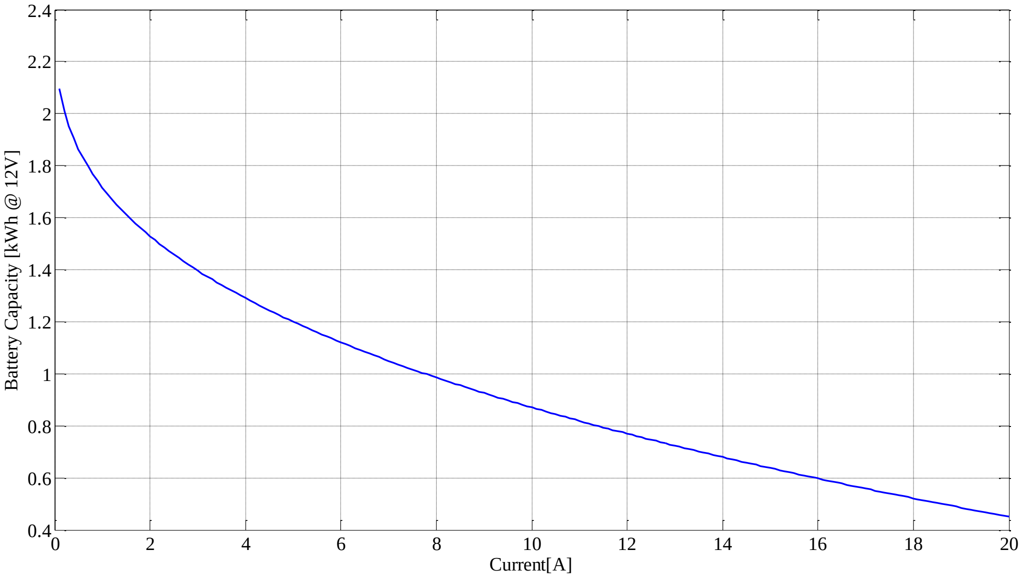


Fig 2.17 Variation in battery capacity for a lead-acid battery of 12V, 1.2 kWh C20.

Thus, discharging a battery with a current under the nominal rate causes a slower SOC decrease, on the contrary discharging a battery with a current over the nominal rate leads the battery to a faster discharge. In other words Peukert equation models the real behaviour of the battery in which the capacity is not fixed but variable according to the current imposed (Fig 2.17). A kWh asked by the load under the nominal current rate is like a kWh removed from an ideal bigger battery that causes a lower variation in the state of charge. Peukert equation finds a way to describe this parallelism reporting the real variations in the energy content of the battery under consideration.

In literature some authors [67] have criticised the accuracy of this method explaining that Peukert equation is strictly applicable to batteries discharged at constant temperature and constant discharge current (i.e. results of Fig 2.17 can be obtained only if the imposed current does not vary). When applied to a battery with a variable discharge rate and changing operating temperature using average or effective current, it generally results in an underestimation of the remaining capacity. To be more accurate, equivalent circuit battery models need to be used since they model the batteries in the shape of electronic circuits. There are many models proposed, [22] the most famous of which is the Thevenin battery model. However, it has not been recognized the need to continue in the further development of this topic as it has been not detected as necessary for the purposes of the application which is presented in Chap. 4.

Battery model: lifetime determination

As expressed in Equation (2.28) the Net Present Cost of an “Off-Main-Grid” Photovoltaic system is influenced also by the number of replaced batteries during the life cycle. At the light of this, estimating the lifetime of a battery become fundamental. Manufacturers provide the number of cycles of charge-discharge guaranteed by a battery tested at constant current in accordance with a predetermined minimum state of charge. However normally a battery is not used at a constant charge or discharge rate and, as found in practice, the effect on the useful life also depends on the state of charge in which the discharge starts. In literature a lot of method to estimate the lifetime of batteries have been considered but the followings are the most used [49]:

Equivalent full cycles to failure

This method defines the end of a battery lifetime when a specified number of full charge-discharge cycles are reached. The estimation of the lifetime consists of adding the charge cycled by the battery and updating the number of full cycles as follows:

$$f_{Bat,LT}(t) = f_{Bat,LT}(t-1) + \frac{I(t)\Delta t}{C_{Bat,rated}} \tag{2.36}$$

The battery will reach the end of lifetime when:

$$f_{Bat,LT}(t) = f_{Bat,LT}{}^{END} \tag{2.37}$$

Whit $f_{Bat,LT}{}^{END}$ the chosen number of cycles to failure is defined by the IEC standard [68].

“Rainflow” cycles counting

This is the method of cycles counting known as ‘‘rainflow’’, based on Downing’s algorithm [69] and is more complex and precise than the previous. The method of cycles counting is based on counting the charge/discharge cycles Zi corresponding to each range of the DOD (split in m intervals) for a year. For each interval there is a number of Cycles to Failure (CF_i) obtained from Fig 2.7. Battery duration, in years, can be calculated as follows:

$$Life_{Bat} = \frac{1}{\sum_{i=1}^{m} \frac{Z_i}{CF_i}} \tag{2.38}$$

The weighted ageing model

Lifetime data by manufacturers are based on well-defined test conditions. Cycle lifetime is simply determined by discharging the battery with a constant current to a certain depth of discharge and a subsequent full charge with a given charging regime. However, in real application, the operating conditions typically deviate from these standard operating conditions and the Ah throughput of the battery may be more or less damaging than during the standard operating conditions.

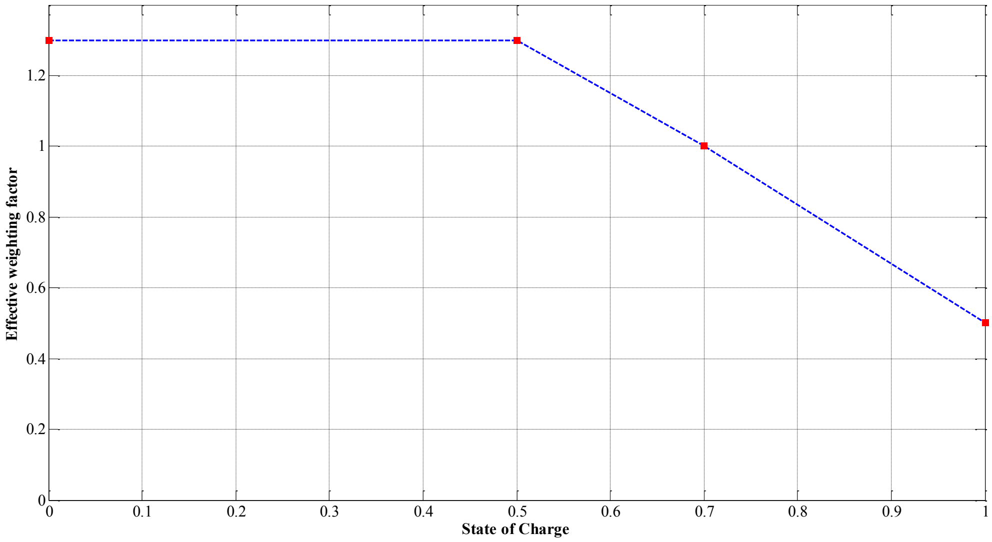


Fig 2.18 Relationship between effective weighting factor and SOC [70].

The weighted Ah ageing model [71] takes these deviations into account and makes the assumption that the battery is at the end of its lifetime once the weighted Ah throughput has exceeded the expected unweighted Ah throughput which has been measured under nominal operating conditions. In the model, at each instant of time the effective discharge is the product of the actual ampere-hours delivered and the 'effective weighting' of the discharge. The effective weighting factor is determined from the estimated SOC of the battery at that instant. Fig 2.18 shows the variation of the effective weighting factor with SOC. For example, at an SOC of 0.5, removing 1 Ah from the battery adds 1.3 Ah to the lifetime cumulative total. However, at a SOC of 1, removing 1 Ah will result in only 0.55 Ah being added to the effective cumulative total. This would indicate, as is usually assumed, that batteries are best operated at high SOCs to optimise the lifetime.

2.3.3 *HOMER* software

The *HOMER* Micropower Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide range of applications. *HOMER* models a power system's physical behaviour and its life-cycle cost, which is the total cost of installing and operating the system over its life span. *HOMER* allows the modeller to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs.

HOMER can model grid-connected and off-grid micropower systems serving electric and thermal loads, and comprising any combination of photovoltaic (PV) modules, wind turbines, small hydro, biomass power, reciprocating engine generators, microturbines, fuel cells, batteries, and hydrogen storage. *HOMER* performs three principal tasks: simulation, optimization, and sensitivity analysis.

The simulation process serves two purposes. First, it determines whether the system is feasible. *HOMER* considers the system to be feasible if it can adequately serve the loads and satisfies any other constraints imposed by the user. Second, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. *HOMER* steps through the year one hour at a time, calculating the available renewable power, comparing it to the electric load, and deciding what to do with surplus renewable power in times of excess, or how best to generate additional power in times of deficit. When it has completed one year's worth of calculations, *HOMER* determines whether the system satisfies the constraints imposed by the user on such quantities as the fraction of the total electrical demand served the proportion of power generated by renewable sources, or the emissions of certain pollutants. *HOMER* simulates how the system operates over one year and assumes that the key simulation results for that year (such as fuel consumption, battery throughput, and surplus power production) are representative of every other year in the project lifetime, it does not consider changes over time, such as load growth or the deterioration of component performance with aging. The quantity *HOMER* uses to represent the life cycle cost of the system is the total net present cost (NPC). This single value includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present.

The optimization process determines the best possible system configuration. In *HOMER*, the best possible, or optimal, system configuration is the one that satisfies the user specified constraints at the lowest total net present cost. Finding the optimal system configuration may involve deciding on the mix of components that the system should contain, the size or quantity of each component, and the dispatch strategy the system should use. In the optimization process, *HOMER* simulates many different system configurations, discards the infeasible ones (those that do not satisfy the user-specified constraints), ranks the feasible ones according to total net present cost, and presents the feasible one with the lowest total net present cost as the optimal system configuration.

A sensitivity analysis reveals how sensitive the outputs are to changes in the inputs. In a sensitivity analysis, the *HOMER* user enters a range of values for a single input variable. One of the primary uses of sensitivity analysis is in dealing with uncertainty. If a system designer is unsure of the value of a particular variable, he or she can enter several values covering the likely range and see how the results vary across that range.

Fig 2.19 illustrates the relationship between simulation, optimization, and sensitivity analysis. The optimization oval encloses the simulation oval to represent the fact that a single optimization consists of multiple simulations. Similarly, the sensitivity analysis oval encompasses the optimization oval because a single sensitivity analysis consists of multiple optimizations.

Physical modelling

In the following subsections, the attention is focus on describing how *HOMER* models an “Off-Main-Grid” Photovoltaic system in terms of load, resource and main components.

<u>Load</u>

HOMER models different types of loads. In the case of SAPV system, two are the load that the software uses: primary load and deferrable load. Primary load is electrical demand that the power system must meet at a specific time. Electrical demand associated with lights, radio, TV, household appliances, computers, and industrial processes is typically modelled as primary load. When a consumer switches on a light, the power system must supply electricity to that light immediately, the load cannot be deferred until later. If electrical demand exceeds supply, there is a shortfall that *HOMER* records as unmet load. The *HOMER* user specifies an amount of primary load in kilowatts for each hour of the year, in terms of a single 24-hour profile that applies throughout the year, or different profiles for different months and different profiles for weekdays and weekends. Deferrable load is electrical demand that can be met anytime within a defined time interval. Water pumps, icemakers, and battery-charging stations are examples of deferrable loads because the storage inherent to each of those loads allows some flexibility as to when the system can serve them.

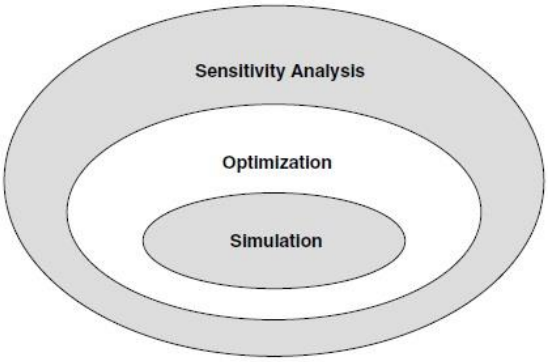


Fig 2.19 Conceptual relationship of simulation, optimization and sensitivity analysis [72].

Solar resource
To model a system containing a PV array, the *HOMER* user must provide solar resource data for the location of interest. Solar resource data indicate the amount of global solar radiation (beam radiation coming directly from the sun, plus diffuse radiation coming from all parts of the sky) that strikes Earth's surface in a typical year. The data can be in one of three forms: hourly average global solar radiation on the horizontal surface (kW/m^2), monthly average global solar radiation on the horizontal surface (kWh/m^2 day), or monthly average clearness index. If the user chooses to provide monthly solar resource data, *HOMER* generates synthetic hourly global solar radiation data using an algorithm developed by the authors in [73].

PV array
HOMER models the PV array as a device that produces DC electricity in direct proportion to the global solar radiation incident upon it, independent of the voltage to which it is exposed (it assumes that a maximum power point tracker is present in the system). For each hour of the year, *HOMER* calculates the global solar radiation incident on the PV array using the *HDKR* model [74]. This model takes into account the current value of the solar resource (the global solar radiation incident on a horizontal surface), the orientation of the PV array, the location on Earth's surface, the time of year, and the time of day. Then, *HOMER* calculates the power output of the PV array using the equation

$$P_{PV}(t) = f_{PV}\, Y_{PV}\, \frac{H_T}{\mathrm{h}} \tag{2.39}$$

Where, f_{PV} is the PV derating factor, Y_{PV} the rated capacity of the PV array (kW), I_T the global solar radiation (beam plus diffuse) incident on the surface of the PV array (kW/m^2), and h is 1 kW/m2, which is the standard amount of radiation used to rate the capacity of the PV array.

Battery bank
HOMER models a single battery as a device capable of storing a certain amount of DC electricity at fixed round-trip energy efficiency, with limits as to how quickly it can be charged or discharged, how deeply it can be discharged without causing damage, and how much energy can cycle through it before it needs replacement. *HOMER* assumes that the properties of the batteries remain constant throughout its lifetime and are not affected by external factors such as temperature. The key physical properties of the battery are its nominal voltage, capacity curve, lifetime curve, minimum state of charge, and round-trip efficiency.

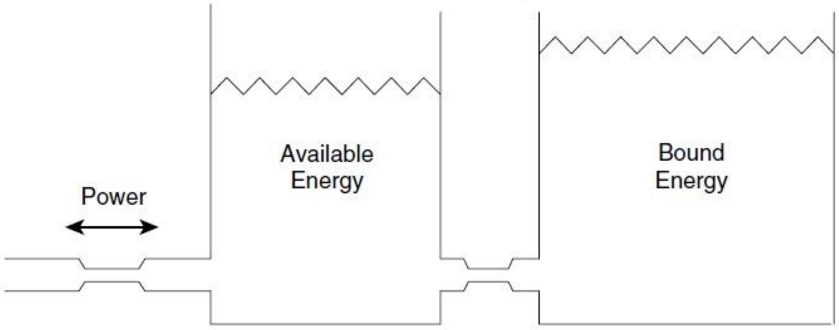


Fig 2.20 Kinetic Battery Model concept [72].

The capacity curve shows the discharge capacity of the battery in ampere-hours versus the discharge current in amperes while the lifetime curve shows the number of discharge–charge cycles the battery can withstand versus the cycle depth, in parallel with what exposed in Fig 2.7 and Fig 2.17. To explains the shape of the typical battery capacity curve, *HOMER* uses the kinetic battery model [75], which treats the battery as a two tank system as meaning that part of the battery's energy storage capacity is immediately available for charging or discharging, but the rest is chemically bound. At high discharge rates, the available tank empties quickly, and very little of the bound energy can be converted to available energy before the available tank is empty, at which time the battery can no longer withstand the high discharge rate and appears fully discharged. At slower discharge rates, more bound energy can be converted to available energy before the available tank empties, so the apparent capacity increases. Moreover, it means that the battery's ability to charge and discharge depends not only on its current state of charge, but also on its recent charge and discharge history. A battery rapidly charged to 80% state of charge will be capable of a higher discharge rate than the same battery rapidly discharged to 80%, since it will have a higher level in its available tank. Concerning the battery lifetime *HOMER* calculates the lifetime throughput curve shown in Fig 2.21 as black dots as follows:

$$Q_{LT,i} = z_i DOD_i E_{Bat,rated} \tag{2.40}$$

Where z_i is the number of cycles at a chosen $\mathrm{DOD_i}$ and $\mathrm{E_{Bat,rated}}$ the rated capacity of the battery. *HOMER* makes the simplifying assumption that the lifetime throughput is independent of the depth of discharge, thus estimates the life of the battery bank simply by monitoring the amount of energy cycling through it, without having to consider the depth of the various charge–discharge cycles. The value that *HOMER* suggests for this lifetime throughput is the average of the points from the lifetime curve above the minimum state of charge. *HOMER* calculates the life of the battery bank in years as:

$$R_{Bat} = min\left(\frac{N_{Bat} Q_{LT}}{Q_{thrpt}}, R_{bat,f}\right) \tag{2.41}$$

Where N_{batt} is the number of batteries in the battery bank, Q_{LT} the lifetime throughput of a single battery, Q_{thrpt} the annual throughput (the total amount of energy that cycles through the battery bank in one year), and $R_{batt,f}$ the float life of the battery (the maximum life regardless of throughput).

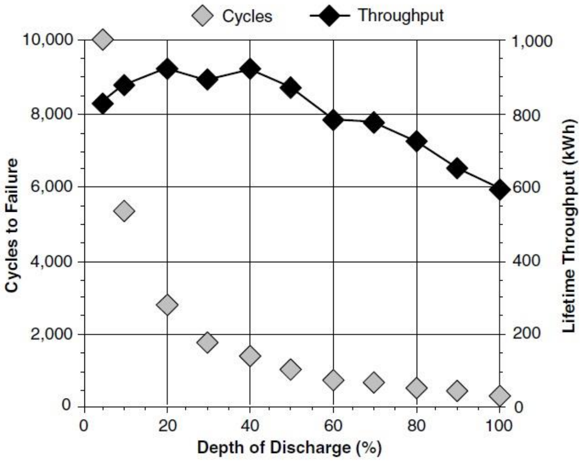


Fig 2.21 Lifetime curve for deep-cycle battery model US-250 [72].

Converter

HOMER can model the two common types of converters: solid-state and rotary. The converter size, which is a decision variable, refers to the inverter capacity, meaning the maximum amount of ac power that the device can produce by inverting DC power. The final physical properties of the converter are its inversion efficiency, which *HOMER* assumes to be constant.

Economic modelling

For each component of the system, the modeller specifies the initial capital cost, which occurs in year zero, the replacement cost, which occurs each time the component needs replacement at the end of its lifetime, and the O&M cost, which occurs each year of the project lifetime. The user specifies the lifetime of most components in years whit the battery exception. *HOMER* uses the total Net Present Cost (NPC) to represent the life-cycle cost of a system. The modeller specifies the discount rate and the project lifetime. *HOMER* uses annualized cost to calculate the levelized cost of energy:

$$C_{ann,tot} = CRF\left(r, R_{proj}\right) NPC \tag{2.42}$$

Where r is the annual real interest rate (the discount rate), R_{proj} the project lifetime, and *CRF()* is the capital recovery factor, given by the equation:

$$CRF\left(r, R_{proj}\right) = \frac{r(1+i)^N}{(1+r)^N - 1} \tag{2.43}$$

Where N is the number of years of the project. *HOMER* uses the following equation to calculate the levelized cost of energy:

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{2.44}$$

Where E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively, that the system serves per year, and $E_{grid,sales}$ is the amount of energy sold to the grid per year. The denominator is an expression of the total amount of useful energy that the system produces per year. The levelized cost of energy is therefore the average cost per kWh of useful electrical energy produced by the system.

Chapter 3

3. Sizing of SAPV Systems: an Appropriate Intuitive Method for Ugandan Context

The main objective of this chapter is to present the activities carried out by the author during the internship period of two months at Village Energy Limited in Uganda, which is one of the Ugandan actors in Stand-Alone Photovoltaic (SAPV) systems installation. After a brief introduction that explains the motivations of the work, the decision support tool developed by the author, named *VE Sizing&Pricing* tool, is exposed as a context-based appropriate intuitive method. Finally, a typical case study is chosen and the design results are compared with those computed with the software *HOMER*.

3.1 Motivations

As explained in Chap. 1 some problems affected the survival of Village Energy: (i) the unfair competition in the Ugandan market, (ii) the low costumer's willingness and capability to pay and (iii) the financial difficulties are the main obstacles to the rise of the company. However, another problem emerges as a clear constraint to the development of business activities, which is a marked slowness operational. Indeed, Village Energy is experiencing an increasing demand of customised systems meaning that more and more frequently the standardized products are not enough to satisfy the client's needs. This fact means that to Village Energy's staff is requested to be able to size a system in the presence of the clients to give them quotation and close deals. The slowness emerges at such this level and is caused principally by two factors:

1. The strong dependence on the chief-technician Steven Muwanguzi, who is the only one that have the capability, thanks to years of practice, to decide which is the size of the system that responds to the customer's desiderata. Indeed, it happens frequently that, when the client comes to the office, Steven is not available because he is working on other installations far away from the office or he is at the market for buying components, etc.. The most of other employees (both technicians and accountants), with no high technical skills and no software which can help them, are not able to take a decision and are forced to ask the client to come back later.

Moreover, sometimes, being them aware that the chief-technician will not be back in the office soon, they ask the client to give as much information as possible before let him leave the office with a promise to be contacted later for a quote. From that moment, an endless number of phone calls begin to Steven to resolve the issue. However, the information collected are often not sufficient and they need to contact later the client;

2. The lack of a price list of components: indeed the problem continues also after having sized the system, because a long dispute on the merit of price of each component starts between technicians and accountants.

Thus, this inefficient process implies the necessity of a long time to close an order, sometimes months pass from the first contact with the client to the final quotation. Nevertheless, in most cases, during this period the client looks around searching for other companies.

In this context, the aim of the author's work has been to develop a tool that help all of the employees of Village Energy to be more independent in decision and capable of giving right quotations to the client after having ordered the information coming from him. In agreement with the management, the new tool should be appropriate for the case of Village Energy having the following characteristics:

1. *Simple*: everyone in Village Energy must understand its potential as well as being able to use it properly.
2. *Fast*: in such a way as to make the employee able to provide the customer the requested quotes in few minutes, following some simple steps.
3. *Flexible*: so that it can adapt to any customer request.
4. *Market-based*: the results of the sizing must be in terms of components that actually exist on the market. All components’ information (size, nameplate data, prices) need to be collected in a database.
5. *Editable in the future*: the database, the sizing approach and the economic assumptions must be able to be modified in the event of a change of corporate strategy.

To respond to the first two characteristics an intuitive method of sizing, in the respect of the current sizing assumption used in the company, has been chosen by the author since it is simple to understand and very fast in giving results if compared to numerical methods. To address the flexibility, the use of already existing software has been rejected since they cannot guarantee the elasticity requested by Village Energy, especially in terms of collecting information from the client. Thus, Microsoft Excel was chosen as starting point to develop the tool, named *VE Sizing&Pricing*, because it is well known and used by all the personnel of the company. The fourth specificity has been implemented by creating a database of components that integrates with the specific results coming from the sizing procedure, having the aim of giving corrected results in terms of components to buy on the market. Finally, to give a response to the last characteristic, a simple guide was written by the author and a simple course on the *VE Sizing&Pricing* tool has been held with everyone in Village Energy.

3.2 VE Sizing&Pricing: a decision support tool

The *VE Sizing&Pricing* comes like a decision support tool. Composed by simple Microsoft Excel sheets, it has been designed by the author to make every employee in Village Energy capable of giving updated quotation in few minutes to each client that enters into Village Energy office to buy a SAPV system. In Fig 3.1 the logical block scheme of the *VE Sizing&Pricing* tool, consisting of four steps, which correspond to four Microsoft Excel sheets to be filled by the user of the tool, is presented to the reader. As shown, the process starts from the customer's needs and finishes with the quotation given to the client.

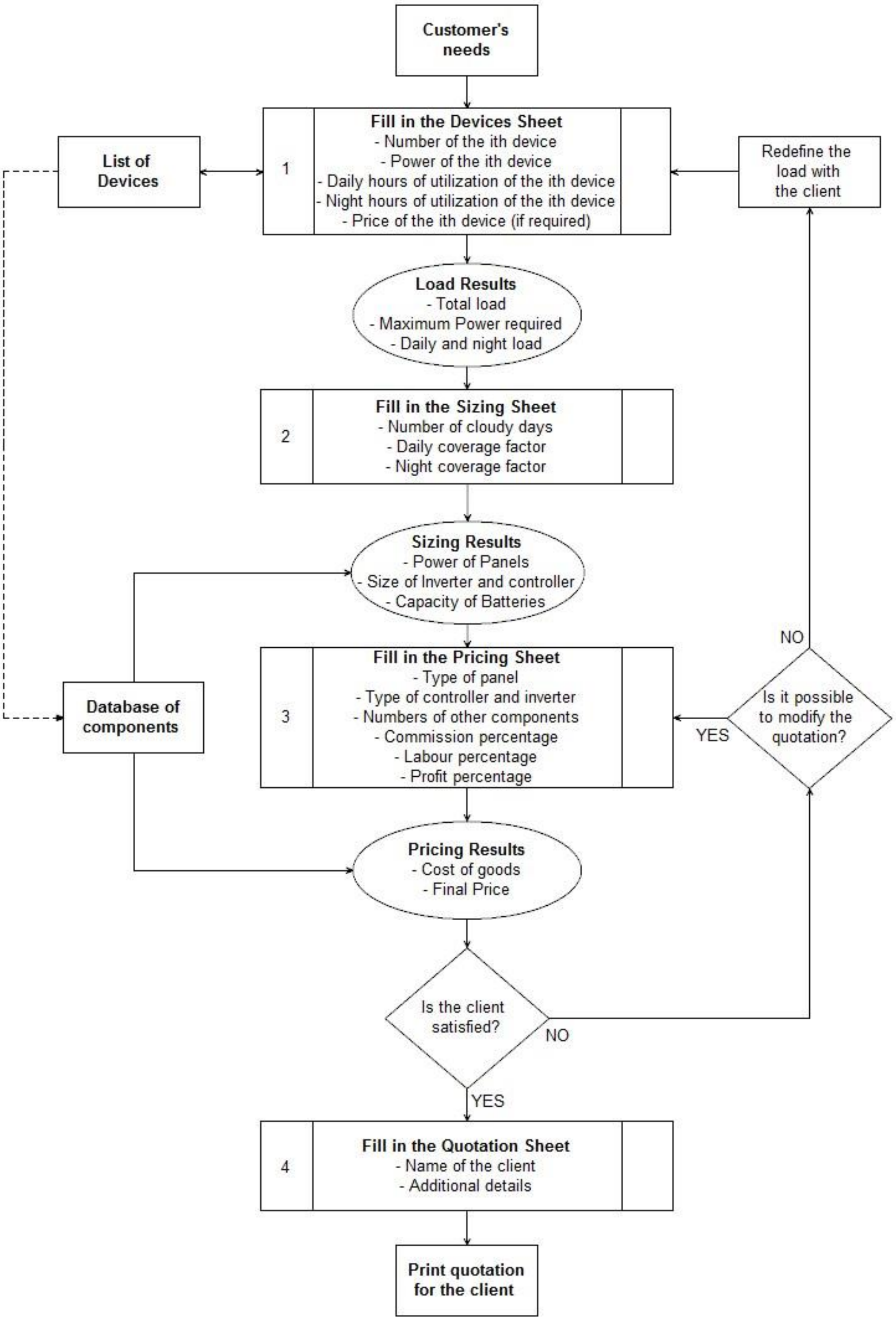


Fig 3.1 *VE Sizing&Pricing*, logical block scheme.

1. The first step involves the interaction between the client and the employee. The customer’s desiderata are ordered in the first Microsoft Excel sheet, named *Device sheet*, in which:
   - For each appliance, information from the client regarding the number, the daily and night hours of utilization needs to be collected by the user to fill an already existing list of common devices. Concerning the power of the *ith* device, sometimes the client does not know this information so the user can refer to the normal value used for same devices that appears in the existing list. Finally, price information about the device need to be put only if Village Energy will buy it for the client (for example: LED bulbs to replace old bulbs), in order to be able to find that information during the pricing phase.
   - An optional passage occurs if something unusual, which is not among the normal devices already present in the list, is asked by the costumer. In this case, the employee has to update the list of devices for future use. This fact affects also the updating of the database. Indeed, if a client asks for example a stereo system powered by an SAPV system, apart from the amplifier, which is the only component that required to be powered, also speakers and connection wires need to be put in the same system.
   - As automatic output of this first step, that are requisite for the following sizing phase, the user can read the load results in terms of total, daily and night load and maximum power required by all the devices.
2. The second step involves results from the *Sizing sheet*, in which:
   - The only variables (i.e. Microsoft Excel cells) that can be changed are the number of cloudy days and the night and daily coverage factor. However, the employee must not change anything because these parameters derive from fixed sizing assumptions, which can vary only after changing in corporate strategy.
   - The user has just to read the sizing results in term of panels’ power, battery capacity and size of the controller and inverter to be installed.
   - The results emerge from the equations of the intuitive method implemented behind the sheet and after that, they are automatically (without the need for user interaction) compared with the information in the database to get the best final sizing results in terms of real parts available in the shops.
3. The third step is represented by filling the *Pricing sheet*, in which:
   - The employee has to choose the type of panels, charge controller and inverter and the number or length of others components scrolling drop-down menus behind corresponding cells (e.g. the length of wires to connect all the components or the number of lamp holders, wall switches and moulded boxes that are needed to complete the installation). Note that, if the user is not sure of certain data, he can refer to already present results deriving from some empirical equations based on previous installations.
   - There is the possibility to vary also profit margin, labour percentage and commission percentage in the case that changes the corporate strategy.
   - The sheet works automatically, taking the correct prices of each component from the database and giving as pricing results the cost of goods and the total price of the system, useful to have idea of the total cost for the company and the price to be given to the customer.
4. The fourth and final step involves a decision because, at this level, two are the possibilities:
   - If the client is satisfied by the price the next and final step is to fill the *Quotation sheet* with additional details and print the quote for the client as appears in Fig B.0.1 in Appendix B.

- If the customer does not agree with the price, the employee must firstly check the *Pricing sheet* in order to reduce the final price. Otherwise, the redefinition of the load in the *Device sheet* with the client is required (especially about the correctness of the hours of use of each appliance), in order to reduce the size of components and consequently the final price.

In the next paragraphs each of the step mentioned above are deeply exposed to better understand the operation of the *VE Sizing&Pricing* tool.

3.2.1 Database

Before going into the merits of the various spreadsheets is necessary to expose the logic followed in the creation of database, which has been intended to be the place in which all technical and cost information can be found. To build it up, the information from all the Village Energy's staff was collected. The database is made by five lists. Four lists of the principal components: panels, batteries, charge controllers and inverters, and one list of all the other components needed to complete the installation of the system under sizing, such as wires, lamp-holders, screws etc...

In Table 3.1 the list concerning the PV modules is exposed. First, the common size of modules that Village Energy buys from usual vendors has been identified. As shown in the table, modules go from the minimum power of 5 W to a maximum power of 240 W. Then, the above modules have been combined to form different array sizes that could address different client's needs, from a minimum power of 5 W to a maximum power of about 1 kW (note that the list has been designed to be extended in case reaching bigger sizes is required). Concerning the prices of the different types of modules, they have been already exposed in Section 1.5. The same structure has been used also to develop the battery list in terms of battery capacities findable on the market and resulting capacity after having combined such these batteries (Table B.0.1).

In Table 3.2 is shown the list of the inverters normally used by Village Energy in its installations. Information regarding power, working voltage and price of each type are put in the table since are useful in phase of sizing and in phase of quotation. In parallel, also charge controllers list has been developed with the type of PWM controllers used by the company and rated current information (Table B.0.2).

Table 3.1 PV array sizes list.

Array Power [W]	Module Rated Power [W]	N°	Array Power [W]	Module Rated Power [W]	N°
5	5	1	**130**	65	2
10	10	1	**140**	70	2
15	15	1	**150**	75	2
20	20	1	**160**	80	2
30	30	1	**200**	100	2
35	35	1	**240**	240	1
40	40	1	**300**	100	3
50	50	1	**360**	120	3
65	65	1	**400**	100	4
70	70	1	**480**	240	2
75	75	1	**500**	100	5
80	80	1	**600**	120	5
100	100	1	**720**	240	3
120	120	1	**960**	240	4

Table 3.2 Inverter list.

Inverter Type	Rated Power [W]	Working Voltage [V]	Price [UGX]
300 W Samlex	300	12	100,000.00
300 W Victron	300	12	450,000.00
600 W Samlex	600	12	150,000.00
600 W Victron	600	12	500,000.00
600 W Genesis	600	12	600,000.00
1000 W Genesis	1000	24	1,000,000.00
2500 W Genesis	2500	32	2,800,000.00
3500 W Genesis	3500	48	4,200,000.00

Finally, an “others components” pricing list (Table B.0.3) has been developed to take into account all the other costs that affect the installation. Actually, remember that Village Energy is not a vendor of solar components, but an installer of complete SAPV system, from panels to the last light. The unit price of components depends on the company strategy. For example, the wires are bought at wholesale price because it is more convenient to buy an entire roll of wire and use a part of it instead of buy the required length of wire for each installation. In contrast, lamp holders are bought in single pieces because the wholesale price is not convenient in terms of quantity to buy.

After building the database in the form of five lists of components, the next step has been to develop the four spreadsheets as mentioned before.

3.2.2 Device sheet

The sizing process starts from the client’s needs. The *Device sheet* has the intent to collect and order all the information that the customer can provide about the devices that he wants to power with the SAPV system. The spreadsheet is in the form of table (Table 3.3) with a list of possible devices. The information required for each *ith* device are: the power, number, daily and night hours of utilization and, if required, the price.

Table 3.3 “Initialized” table of devices with sample data.

Device	Power [W]	N°	Daily hours of Utilization	Night Hours of Utilization	Price [UGX]
Amplifier	8	-	0	4	70,000.00
Ceiling Fan	75	-	4	2	-
Freezer	1000	-	4	3	-
Fridge	300	-	4	3	-
Laptop (Big)	100	-	2	3	-
Laptop (Small)	50	-	2	3	-
LED Bulbs (3 W)	3	-	0	6	10,000.00
LED Bulbs (5 W)	5	-	0	6	15,000.00
Led strips	7.5	-	0	6	14,000.00
PC	250	-	2	3	-
Phone charging	5	-	2	2	-
Pico Projector	18	-	0	4	550,000.00
Printer	40	-	1	1	-
Security Lights	5	-	0	12	15,000.00
Shaver	10	-	1	1	125,000.00
Standing Fans	50	-	4	2	-
Television 14"	75	-	0	4	-
Television 20"	100	-	0	4	-

The user finds the table as “initialized” meaning that is already filled with the usual data obtained from same devices installed in similar systems. In this way, the user can refer to this information if there is any lack or indecision from the customer especially about power and hours of day and night use of the *ith* device. This approach can lead to errors not negligible, because it is known that, for example, the power consumption of a laptop is variable depending on the type. However, this ploy has been detected as the only feasible to standardizes common appliances.

Also in this case, the table can be extended and updated adding new devices according with the customer's needs. The prices of the devices are not to be filled by the user if the device *ith* is already present at the customer’s site of installation. As shown in (Table 3.3) the “initialized” table presents only some prices, which are the ones of the devices that normally Village Energy offer to install for the costumer in order to reduce power consumption; for example LED lights to replace “energy-savers” lights and pico-projectors to replace televisions. In such cases Village Energy has to buy the bulbs and the relative costs are to be taken into account.

Anyhow, regardless of the client's needs and the ability of the seller, the *Device sheet* needs all the information above mentioned to run and gives as outputs the total load of the day (E_L) divided in daily load (E_d) and night load (E_n), and the maximum power consumption of all the devices ($P_{L,max}$), which are calculated as follows:

$$E_d = \sum_{i=1}^{n} P_i N_i h_{d,i} \ ; \ E_n = \sum_{i=1}^{n} P_i N_i h_{n,i} \tag{3.1}$$

$$E_L = E_d + E_n \tag{3.2}$$

Where P_i and N_i are the quantity and the power of each devices *ith*, while $h_{d,i}$ and $h_{n,i}$ are respectively the daily and night hours of utilization of the same device. Note that Uganda is at the equator latitude so the days during the year can be assumed equally divided in 12 hours of night followed by 12 hours of light. Regarding the maximum power consumption, it is the maximum value between the total power required by the devices that are used during the daily hours and the total power during the night.

$$P_{L,max} = max\left(\left(\sum_{i=1}^{n} P_i N_i\right)_d, \left(\sum_{i=1}^{n} P_i N_i\right)_n\right) \tag{3.3}$$

These outputs are fundamental for the next step, which is the sizing phase.

3.2.3 Sizing sheet

The *Sizing sheet* has been developed with the main idea of putting in a digital format all the expertise accumulated by Village Energy during five years of experience on the field. The inputs necessary for the sizing procedure are those coming from the *Device sheet* and the results emerge from the equations behind the sheet.

The sizing method is principally based on the assumptions deriving from lessons learnt and feedback from installations made by the company (Table 3.4). An intuitive approach that is explained in the next paragraphs, appropriated for the case of Village Energy, has been adapted to set up the sizing procedure able to take into account the real components available on the market. The *Sizing Sheet* sizes both systems for only DC loads and systems for AC loads (Fig 3.2). The main results are the power of the PV array, the capacity of the battery bank, the size of the charge controller and, if required, the power of the inverter.

Table 3.4 Village Energy's sizing assumptions.

SIZING ASSUMPTION			
Balance of system efficiency	BOS	90	%
Minimum state of charge of battery	SOC_{min}	40	%
Peak Sun Hours	PSH	6.00	h
Night Coverage Factor	f_n	100	%
Daily Coverage Factor	f_d	20	%
Cloudy Days	cd	1	
Inverter efficiency	η_{Inv}	90	%

Inverter sizing

As happens in the most of cases of customised products, the customer's needs lead to prefer for an AC SAPV system (Fig 3.2). Then, the first step is to size the inverter on the maximum power required by the load taking into account the inverter efficiency. Thus, the minimum inverter's power necessary is given by:

$$P_{Inv,min} = \frac{P_{L,max}}{\eta_{Inv}} \tag{3.4}$$

Then, all the inverters in the database (Table 3.2) are automatically checked and the one that presents a rated power that meet the result from Equation (3.4) with the lowest difference is the inverter that needs to be purchased on the market and installed at the client's site.

$$P_{Inv} = P_{Inv,min} + \min\left(P_{Inv,i} - P_{Inv,min}\right) \tag{3.5}$$

From the database, also the voltage required by the inverter is taken and fixed as the DC voltage of the system V_{Sys} before the inverter.

PV array sizing

The next step is to size the power of the photovoltaic array. According with Equation (2.2) the minimum PV power necessary is given by:

$$P_{PV,min} = \frac{E_L}{PSH \cdot BOS} \tag{3.6}$$

Where the balance of system is set to 0.9 and the Peak Sun Hours at a value of 6 hours as the resulting average of the 12 months of the year.

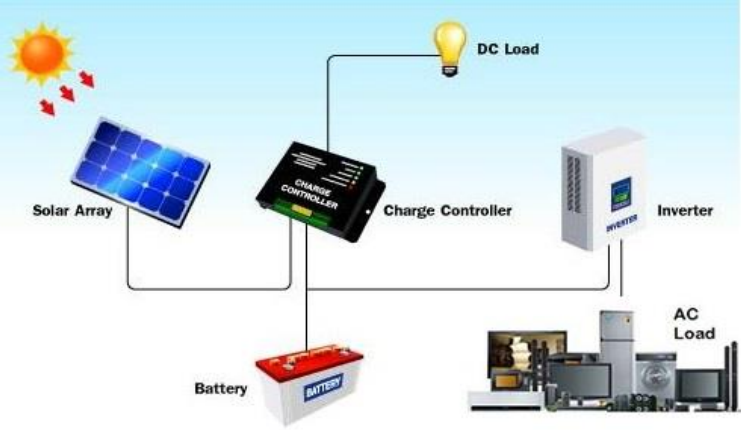


Fig 3.2 Typical layout of Village Energy's installations.

As done for the inverter the database (Table 3.1) is scrolled to find the best combinations of panel of power P_{mod} that form an array that meets the result from Equation (3.6) with the minimum difference.

$$P_{PV} = P_{PV,min} + \min\left(P_{Array,i} - P_{PV,min}\right) \tag{3.7}$$

However the sizing of PV array is not concluded because the DC voltage required by the inverter needs to be respected. Indeed, noting that the majority of modules present in the market are made to work in 12 Volts systems, sometimes more panels need to be put in series to reach the DC voltage imposed by the inverter and the sizing results might change. For example if the result coming from Equation (3.7) is 3 panels of 150 W and the voltage required by the inverter is 24 Volts, this means that at minimum two panels need to be put in series and thus, 3 panels are not sufficient because a fourth panel is needed to form two series of two modules. In such cases another check trough the database is needed to find the best module's rated power that, multiplied for the right number of panels as mentioned above, satisfies the limit imposed by the inverter $n_{Mod,inv}$.

$$P_{mod,inst} = \frac{P_{PV,min}}{n_{Mod,inv}} + \min\left(P_{mod,i} - \frac{P_{PV,min}}{n_{Mod,inv}}\right) \tag{3.8}$$

Thus, the PV power that needs to be installed in Equation (3.7) is corrected by:

$$P_{PV} = P_{Mod,inst}\, n_{Mod,Inv} \tag{3.9}$$

Charge controller sizing

The charge controller's size has been calculated based on an estimation of the maximum current, which derives from the PV array, so the minimum size of the charge controller to be installed should correspond to:

$$I_{CC,min} = \frac{P_{PV}}{V_{Sys}} \tag{3.10}$$

The above calculation is conservative because the charge controllers normally used by the company are not of MPPT technology. Then, the check of Table B.0.2 is done to find the right size of charge controller that needs to be installed at the client's site:

$$I_{CC} = I_{CC,min} + \min\left(I_{CC,i} - I_{CC,min}\right) \tag{3.11}$$

Battery bank sizing

Concerning the battery bank the sizing starts with defining the Energy that need to be stored as following:

$$E_{Storage} = \left(E_d f_d + E_n f_n\right) n_{CD} \tag{3.12}$$

Where E_d and E_n are respectively the daily and night load coming from the *Device sheet* and n_{cd}, f_n, f_d are the number of cloudy days and the night and daily coverage factors that derive from the experience accumulated after years of installation. Normally the coverage factors are fixed at the value of 20% on daily basis and 100% of night basis while no more than one day is assumed to size the battery. This means that Village Energy's SAPV systems are not sized to take in account climate contingency. Equation (3.13) gives the minimum total capacity in Ah required considering the system voltage and a minimum state of charge of 40% set to preserve batteries from over-discharge.

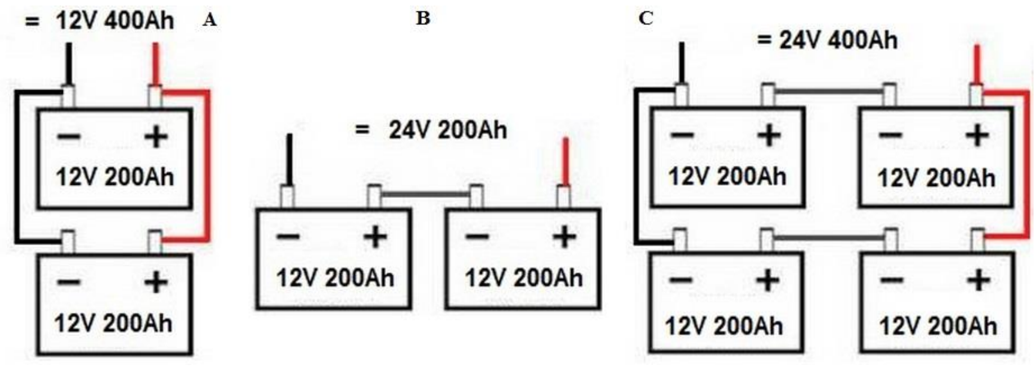


Fig 3.3 Sample of battery sizing.

Note that no battery efficiency is present in that equation, a simplification further amplified since PWM technology does not allow all the energy coming from the PV array to fill the battery, that the author has agreed to keep because, if compared with the reference Equation (2.3) the fact that in the calculation of $E_{Storage}$ there is also a part of the daily load brings a sort of compensation to that negligence.

$$C_{B,min} = \frac{E_{Storage}}{(1 - SOC_{min})V_{Sys}} \tag{3.13}$$

Then, the database (Table B.0.1) is checked to find the best combination of batteries of capacity C_{Bat} available on the market (12 Volts only) that need to be put in parallel in number of $n_{Bat,par}$ to meet the capacity of Equation (3.13) with the minimum difference.

$$C_B = C_{B,min} + \min\left(C_{Bat,Tot,i} - C_{B,min}\right) \tag{3.14}$$

But, even in this case, the DC voltage required by the converter must be respected. For example assume that the capacity required C_B is of 400 Ah and the voltage of the system to be respected is 24 Volts. After checking in the database, the combination of components on the market that meet this requisite of capacity are 2 Batteries of 200 Ah at 12 Volts (Fig 3.3-A), however to meet the requisite of voltage 2 batteries of the same capacity of 200 Ah need to be put in series (Fig 3.3-B). Thus, the final number of batteries of capacity C_{Bat} that need to be installed can be calculated as follows:

$$n_{Bat} = \frac{V_{Sys}}{V_{Bat}}\, n_{bat,par} \tag{3.15}$$

Therefore, at the client's site a total capacity of C_B at V_{Sys} made of n_{Bat} of capacity C_{Bat} at V_{Bat} will be installed, that, referring to the example just done, it means that a total capacity of 400 Ah at 24 Volts made of 4 batteries of 200 Ah at 12 Volts will be installed (Fig 3.3-C).

3.2.4 Pricing sheet

The *Pricing sheet* takes quantitative data from the two previous spreadsheets and the price information from the database to help the employee to draw up the quotation for the client. The sheet can be easily modified by the user taking advantage from the fast drop-down menu that recall the elements present in the various lists of components in the database. The sheet is divided in four blocks:

Table 3.5 *Pricing sheet*, principal components (sample).

Components	**Type**	**No./Qty**	**Rating**	**Unit cost [UGX]**	**Total cost [UGX]**
Panel [W]	**Polycrystalline**	2	240	720,000.00	1,440,000.00
Battery [Ah]	**ABM**	1	200	950,000.00	950,000.00
Charge Controller [A]	**30 AMP ASE**	1	30	150,000.00	150,000.00
Inverter [W]	**300 W Samlex**	1	300	100,000.00	100,000.00

1. Principal components: in this part the user finds copied the results of the *Sizing sheet* in terms of rating and quantity of each component (modules, batteries, charge controller, inverter). At this level the user, if he disagrees with the results or if he is able to size by himself, he can change them to his responsibility. This feature has been implemented to make sure that the results of the previous sheets represent useful information for the novice user but not binding, because the *Pricing sheet* must be able to work independently. Anyhow, at minimum, the user has to decide the quality of the component. For example referring to Table 3.5, if the *Sizing sheet* says that 1 module of 240 W is needed, the user has to choose if this panel will be of monocrystalline or polycrystalline technology scrolling a drop-down menu behind the corresponding cell in the "Type" column. The user has to repeat the same procedure also for charge controllers and inverters. Regarding battery, at the moment Village Energy use only lead-acid type from ABM, but it is not excluded that in the future things will change and, after updating the database, it will be possible also to change the type of storage. Note that by default the options are set on the solution that presents the lower cost. After that, the sheet takes automatically unit cost from the database to calculate the total cost of each component.
2. Devices: when filling the *Device sheet*, as mentioned previously, the prices of the appliances are to be put by the user only if the customer wants village energy takes charge of the purchase of the *ith* device. If, for example, Village Energy has to buy the LED lamps for the client, in the *Pricing sheet* the cost of these appliances is taken into account automatically.
3. Others components: as shown in Table 3.6, apart from the principal components, there is also the need of other components that must be purchased at the market to make systems that work correctly as wires, sockets, wall switches, etc.. Actually, remember that Village Energy is not only a vendor of solar components, but also an installer of complete SAPV system, from panels to the last light, so if the client requests it, they install or change all the connections for each device he wants to power. Also in this case, the user can refer to pre-calculated quantity for each components following empirical equations or change them in others values. For example, it has been estimated that on average 10 metres of 1.5 mm wire (starting from the base-wire) is required to install each lights. As usual, the sheet works automatically and takes the right price from the components database. When the filling is finished the total cost of goods appears as the sum of the prices of all components.
4. Economics: this is the last part, the assumptions of which are derived from business strategies. The profit margin and commission to who has gained the costumer (who may be outside village energy staff) are calculated directly from the cost of goods. The administration fees are, on the contrary, calculated from the final price, which represents the main output and purpose of the *Pricing sheet* since is the only information that the client wants to know.

Table 3.6 *Pricing sheet*, others components (sample).

Components	Type	No./Qty	Rating	Unit cost [UGX]	Total cost [UGX]
Wall switch	-	12	Pieces	2,000.00	24,000.00
Lamp holders	-	12	Pieces	2,000.00	24,000.00
Wire 16mm	-	30	Metres	5,000.00	150,000.00
Wire 2.5mm	-	240	Metres	2,000.00	480,000.00

3.2.5 Quotation sheet

The final step, after having satisfied the client expectation in term of price, it is to fill the *Quotation sheet* which takes automatically all the information from the previous sheet ordering them in a printable layout for the client as shown in Fig B.0.1 in Appendix B. The user has only to put the name and check if some mistake has occurred in the automatic copy from the *Pricing sheet*. The client can visualize all the information he needs in a single sheet of paper, which presents the Village Energy logo in the upper part. Components that the company will install at his site, the final price to pay and the relative cost of labour are showed in a clear list. In the last part notes are specified, like the validity of the quote under consideration, the timing for the installation after payment, the guarantees on components and the costs not included.

3.3 Case study: rural household in Soroti

In the next sections, a typical case study of a customised system is exposed since the *VE Sizing&Pricing* tool has been developed to give a fast response in particular to those clients that want SAPV systems, the sizes of which are not in the range of the standardized products available in the company's list (Table 1.6).

The case study is located in Soroti, in the central-east district of Uganda, a small but expanding town in strong economic growth where the electric grid reaches only business activities and few houses in the city centre. The climate potential of the region is interesting, the stable and sunny weather with high monthly mean values of insolation, make Soroti the ideal place for solar business. Indeed, in that place, where Village Energy has a regional office, the local employees are experimenting a growing demand of customised systems. The majority of households use diesel generators (Genset) to bring electricity in their houses, but nowadays, thanks to solar company like Village Energy, they are realizing the opportunity to shift towards SAPV systems.

The typical client that comes to the Soroti office asking for a SAPV customised system is a private client that lives in the rural area surrounding the city, whose aim is to power the appliances already present in his house where he lives with his family. The household has been chosen composed by 8 people that live in an average home with bedrooms, kitchen, bathroom and a living room [19]. Normally, the devices requiring power that it is possible to find in such family context are:

- Inside lights: to illuminate each rooms;
- Security lights: in Uganda is very common to have outside lights switched on for all the night for security purpose.
- Phone charging: the possibility to recharge phones in Uganda is fundamental because the credit system is alimented by the use of phones.
- PC or Laptop: technology is becoming relatively widespread and cheaper. However, these appliances are normally recharged in offices or schools.

- Television: to listen news and watch sport matches, used especially in the evening hours.
- Fridge: normally small to preserve meat and drinks.
- Ceiling or Standing fan: to be used in the central hour of the day.

Given the case study, the results coming out from the *VE Sizing&Pricing* tool are exposed, followed by coherent results coming from *HOMER*. A final comparison between results, based on the experience gained by the author after two months spent in the operational reality of Village Energy Ltd, is discussed.

3.3.1 Results with VE Sizing&Pricing

In the next sections the four steps exposed above, necessary to size a SAPV system with the *VE Sizing&Pricing* tool are retraced in order to give quantitative results of the case study under consideration.

Load results

The collection of the load information from the client is the first step in order to obtain the load results from the *Device sheet*. Being a case study, some assumptions have been done by the author based on the usual suggestions of the company:

- Inside Lights: normally Village Energy offers to replace all the bulbs already present in the house to 5 W LED ones, which are very bright and at the same time they reduce the power consumption. Moreover, if the wire connections are not in good condition the company replace all the electrical system. In this case, of study both of these aspects are taken as effective. The total number of lights is chosen in number 8: 3 lights in the bedrooms, 1 in the kitchen, 2 in the living room, 1 in the bathroom and 1 in the corridor. The hours of utilization are only the evening hours.
- Security lights: the assumption is to provide one light (the bright LED bulbs of 5 W) for each side of the house. Thus, 4 lights for the 12 night hours are the data to be put in the device table.
- Laptop: the presence of two laptops of 50 W is assumed. The SAPV system must be able to recharge them assuming that they are used 3 hours during the day and 2 hours in the evening for studying and ludic purpose.
- Phone charging: the assumption is to be able to recharge two phones at the same time for two hours both during the night and during the day. The common power consumption of a mobile phone (5 Volts, 1 Amp) of 5 W is assumed.
- Television: one 20 inches 100 W television switched on only during evening hours is assumed.

Table 3.7 Case study, load information grouped in the *Device sheet*.

Device	Power [W]	N°	Daily hours of Utilization	Night Hours of Utilization	Price [UGX]
LED Bulbs	5	8	0	6	15,000.00
Security Lights	5	4	0	12	10,000.00
Laptop	50	2	3	2	-
Phone charging	5	2	2	2	-
20" TV	100	1	0	4	-
Fridge	300	1	4	3	-
Standing Fans	50	1	4	0	-

Table 3.8 Case study, *Device sheet* results.

LOAD RESULTS		
Total Load	3720	Wh
Total Night Load	2000	Wh
Total Daily Load	1720	Wh
Maximum Power Required	570	W

- Fridge: one small 300 W fridge is assumed to work for seven hours during the day, not equally distributed due to different ambient temperature during daily and night hours.
- Standing Fan: one 50 W fan, that can be moved where necessary, is assumed working 4 hours only during the light hours.

All the above information are collected in Table 3.7 in the *Device sheet*. Then, automatically the load results (Table 3.8) are calculated following Equation (3.1-3): the total day load is of about 4 kWh and the maximum power required is of about 600W.

Sizing results

The second step is to size the SAPV system for the client. The sizing results are exposed in Table 3.9. Given the basic sizing assumption (Table 3.4), the size of the inverter, accordingly with the maximum power required, is 1000W. The voltage of the DC bus is consequently set to 24 Volts respecting the specifications in Table 3.2. Concerning the PV array, the power required is approximately of 690W that can be met by 3 modules of 240 W each. However these solution doesn’t respect the voltage on the DC bus, so the best combination become the one composed by 4 modules of 240 W each, for an overall power installed of 960W. The charge controller size is therefore equals to 40Amps according to Equation (3.11). Finally, regarding the battery bank, the minimum capacity required is of about 163 Ah at 24 Volts, so two of 200 Ah at 12 Volts battery are put in series to meet that capacity and voltage requirements. The overall results are resumed in Table 3.9.

Table 3.9 Case study, *Sizing sheet* results.

INVERTER SIZING		
Inverter power to be installed	**1000**	**W**
Voltage of the DC bus	24	V
PV ARRAY SIZING		
Minimum nominal power required	688.89	W
Rated power of each panel installed	240	W
Number of installed panels of the same rated power	4	
PV array power to be installed	**960**	**W**
BATTERY BANK SIZING		
Energy of storage	2.34	kWh
Minimum capacity of batteries to be allocated	162.78	Ah
Rated Capacity of each battery installed	200	Ah
Number of installed batteries of the same rated capacity	2	
Battery Bank capacity to be installed	**200**	**Ah**
CHARGE CONTROLLER SIZING		
Maximum current	40	A
Charge controller to be installed	**40**	**A**

Table 3.10 Case study, *Pricing sheet* main results.

Sub-Total Principal components	6,460,000.00	UGX
Sub-Total Devices	180,000.00	UGX
Sub-Total Others components	684,000.00	UGX
Total Cost of goods	**7,324,000.00**	**UGX**

Pricing results

The third step is to calculate the final price for the client. The pricing results are summarized in Table 3.10 while the complete results with the contribution from single components are exposed in Table B.0.4 in Appendix B. Note that the contributions from corporate decisions, such as profits and administrative costs, have been left out of the case study, so the final price coincides with the total cost of goods which is composed by the cost of the components, which have been sized in the previous section, the cost of the devices to be installed and the cost of all the others components necessary to complete the installation. As shown in Table 3.10 the costs of the principal components cover the 88% of the total cost of goods.

Economic feasibility compared to small diesel generator

To better understand the potential and the consequential opportunities of the installation of such a SAPV system like the one analysed in the case study, it is interesting to compare the same household facing the choice whether to install the SAPV system or a traditional Genset. With some important assumptions (Table 3.11), among which there are: the investment period set to 10 years, the batteries' replacement and check on the system guaranteed by the company every three years and information on the Genset, it is possible to calculate the return on investment of the SAPV system. The main differences between the two solutions are:

1. The initial investment cost: that is strongly in favour of the genset.
2. The operative costs: which, on the contrary, are in favour of the SAPV system despite the replacement of 4 battery bank in 10 years, due principally to the high cost of fuel necessary to run the genset.
3. The Genset would have definitely a higher dispatchability than the SAPV system that has to deal with the uncertainty of the solar resource. However, on the field, has been noticed that the poor quality of the diesel engines normally used and the difficulty in obtaining fuel, smooth out these differences in reference at a rural contexts such as the one into consideration.

Table 3.11 Assumption on investment analysis [76].

ASSUMPTIONS		
Life-Cycle time of SAPV system	10	years
Battery replacement (every)	3	years
Real interest rate	6	%
Fuel cost savings on load basis	840	UGX/kWh
Power of Diesel Genset	700	W
Specific cost of Diesel Genset	1250	UGX/W
Investment cost	875,000.00	UGX
O&M (% on Investment cost)	10	%
Life-Cycle time of Diesel Genset	5	years

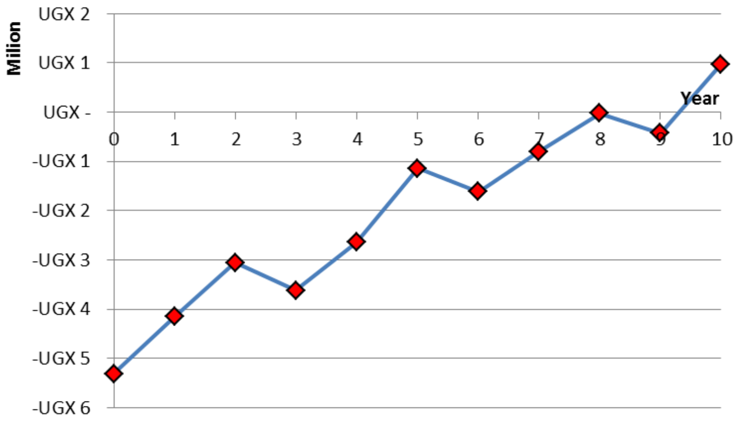


Fig 3.4 Case study, economic feasibility of SAPV system compared to traditional Genset.

The comparison of the two different investments is shown in Fig 3.4 where the return on the investment of the SAPV system has been calculated considering as positive cash flows (savings) all the costs that have been avoided for the Genset operations. The SAPV system appears to be competitive on a 10 years perspective. This conclusion acquires even more importance when is considered that there is no presence of any incentive or aid on investment in renewable energies from responsible institutions.

It is emphasized that this comparison analysis is not currently implemented in the *VE Sizing&Pricing* tool. As a future development, the collection of additional information from the customer about the current energy costs to automatically provide a comparative analysis with information about return on investment, should be taken into consideration in order to provide more details to the customer and let him decide not only based on the cost of investment.

It should also be noted that, in the reality, the high initial investment cost to buy a SAPV system restrains the choice of the client. This aspect is emphasized by two big limitations:

- The difficulties in accessing credit: that limit the economical possibilities of the client;
- The uncertainty of the future: which afflicts both counterparties. Indeed, it is difficult for the customers to view their investment over 10 years if they did not have the security of economic stability during that period, while the same reason in Village Energy context make it impractical to accept payment in instalments or other formulas for the benefit of the customer.

However, a part from context-based and cultural constraints, the above analysis has demonstrated how SAPV system can be already competitive in Uganda as in many others LDCs.

Quotation

The final quote printed for the client is reported in Fig B.0.1 in Appendix B. As appears in the last row before the final price the labour cost is not present since, as mentioned before, administrative costs have been left out of the case study to leave all the analysis independent from the particular corporate strategy.

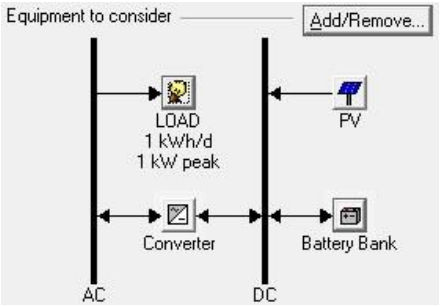


Fig 3.5 *HOMER* default layout for SAPV systems.

3.3.2 Results with *HOMER*

In the next lines, the results computed with the software *HOMER*, as one of the most widely used software in the field and in academia, are presented in order to understand the differences on the same case study with the tool developed by the author. The purpose has been to understand the adaptability and the practicability of the software in a specific context such as the one in which Village Energy operates. To be able to compare the results of *HOMER* with those already exposed from the *VE Sizing&Pricing* tool, the logic has been to set the software in such a way that it could be used to size a system like the one in the case study under consideration. In this perspective and being conscious that HOMER works like a numerical methods, the default settings and layout (Fig 3.5) has been modified substantially to describe the real operational context. In particular:

1. <u>Load curve</u>: *HOMER* requires the hourly load profile. Thus, based on the field experience of the author and the context data collected, starting from the daily and night hours of utilization gathered in the *VE Sizing&Pricing* tool, it has been possible to reconstruct such profile as shown in Fig 3.6. Note that the energy contribution of the fridge, which represents the device with the biggest power consumption, has been calculated dividing the daily and night total energy consumption in equal parts on the daily and night hours. This means that the power absorption of the same appliances is reduced by the ratio of the daily and night hours reported by the client and the total daily and night hours in a day. For example, if the hours of utilization of the fridge (300 W) during the daily hours (12 hours) are in number 4, it follows that the energy consumption is of 1200 Wh. Considering the approach of what above, 100 Wh are allocated for each light hours and consequently power consumption is reduced by 4 times.

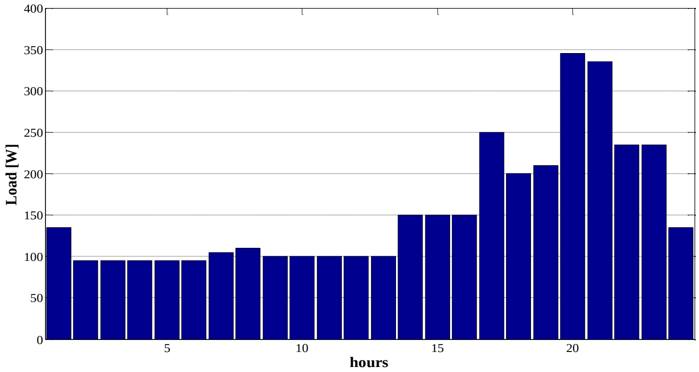


Fig 3.6 Case study, *HOMER* load curve.

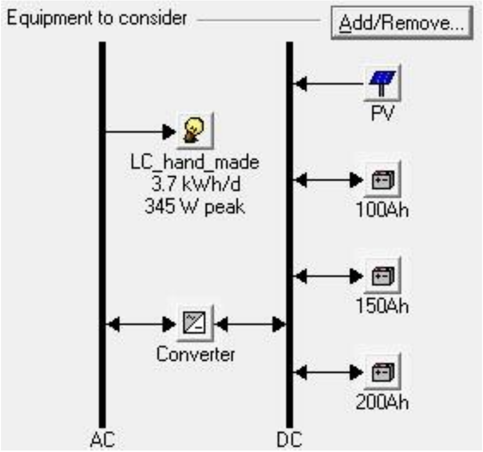


Fig 3.7 Case study, *HOMER* layout for SAPV systems in the real context.

2. <u>Solar resource</u>: *HOMER* requires the specific mean daily solar irradiation on horizontal surface values of the 12 months of the year. Data for the same location has been taken on the website of the NASA atmospheric science data center [66]. It is noticed that the average of those data is equals to 5.94 kWh/m^2 day which is comparable with the 6 PSH assumed in the *VE Sizing&Pricing* tool. Then, *HOMER* generates synthetic hourly global solar radiation data using an algorithm described in [73] which take into account also climate variability.
3. <u>DC voltage</u>: in the *VE Sizing&Pricing* tool the DC voltage is determined by the specifications of the inverter to be installed. In *HOMER* it is not possible to set this feature so the inverter has been imposed equal in power, performance and cost to that one resulting from the *VE Sizing&Pricing* tool. Consequently, to make sure that even in *HOMER* photovoltaic panels and batteries must take into account the voltage set by the inverter some ploys has been implemented, as explained in the next points.
4. <u>PV array</u>: the database of modules available on the market has been put in *HOMER* in order to have the sizes of panel to be tested by the software. This passage has been done in such a way that the particular power under simulation results from the sum of powers of at least the number of modules that returns the right DC voltage.
5. <u>Battery bank</u>: *HOMER* presents an internal database of batteries that can be updated with new ones, so the batteries database as represented in Table B.0.1 has been inserted in the software creating a correspondent numbers of batteries modelled following the ideal approach with a maximum float life of 3 years. The lack of versatility in this case is represented by the fact that it is possible to test different types of battery with different costs and capacity, not necessarily obtainable by combining a single type of battery, only assuming that several batteries are effectively connected to the PV array. Thus, the three larger batteries in the database of Village Energy has been chosen, as the most appropriate in relation to the case study, and simulated with the different sizes of PV array. Consequently the layout in *HOMER* changes to the one represented in Fig 3.7. Note that HOMER does not make working the three represented batteries simultaneously but only one for each simulation. Moreover, regarding the sizing methodology, there is no possibility to take into account the criterion of Village Energy that uses the daily and night coverage factor to size the capacity of the batteries. Thus, as these factors kept into consideration the lack of a batteries' efficiency, the round-trip efficiency, as it appears in *HOMER* battery's menu, has been set to the value of 80%.

6. <u>Charge controllers costs</u>: since *HOMER* does not size the charge controller for the user it does not allow to consider the cost of this component, which varies according to the varying sizes of PV array tested. The solution has been to incorporate the cost of the charge controller to be matched to each PV array in the cost of the same PV array under simulation.
7. <u>Others costs</u>: cost of devices and others components need to be calculated apart and put in the economics specification as fixed cost for all systems simulated.

As explained in Section 2.3.3 *HOMER* works like a numerical methods in which different systems, (i.e. different combinations of panels and batteries), are simulated on yearly basis and a common criterion is used to choose the best combination that addresses the load. *HOMER* steps through the year one hour at a time and calculate the available renewable power, comparing it to the electric load. The battery bank absorbs energy when the PV power output exceeds the load, and discharges energy when the load exceeds the PV power output as represented in Fig 3.8. The graph shows how the battery bank finds hard to recharge during two consecutive cloudy days, January 4–5, indeed the blue line, that represents the state of charge is unable to reach the 100% as it happens for the two previous sunny days, January 3–4. The depletion of the battery means that system cannot supply the entire load on the same days, in fact the green line, which represent the total load required by the client, is overlapped by the red line showing load unsatisfied. *HOMER* records such energy shortfalls and at the end of the simulation determines whether the system supplied enough of the total load to be considered feasible according to user-specified constraints.

In *HOMER*, the best possible system configuration is the one that satisfies the maximum Loss of Load Probability imposed by the user at the lowest total Net Present Cost. Thus, in Table 3.12 the sizing results are exposed as the best systems that address the load at different LLP. For Example, the first result which is composed by a PV array of 480 W, a Battery bank made of two batteries of 100 Ah and an investment cost of about 4.6 million of Ugandan Shillings is the system that satisfies the load with less than the 50% of unmet load with the least value of NPC.

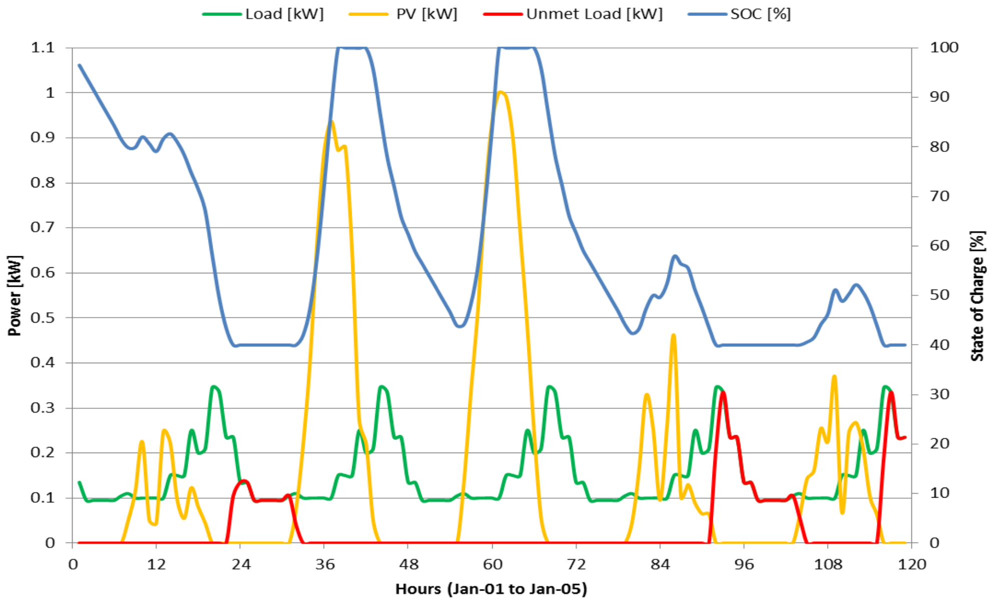


Fig 3.8 Case study, *HOMER* simulation outputs.

Table 3.12 Case study, *HOMER* results.

PV [W]	C_{Bank} [Ah]	n° bat	C_{Bat} [Ah]	Investment cost [UGX]	NPC [UGX]	LLP
480	100	2	100	4,593,667.00	6,181,461.00	50%
600	100	2	100	5,013,667.00	6,601,461.00	40%
720	150	2	150	6,163,667.00	8,951,127.00	30%
960	150	2	150	7,003,667.00	9,791,126.00	20%
960	200	2	200	7,323,667.00	10,675,675.00	10%
960	300	4	150	8,583,667.00	14,158,586.00	5%
960	800	8	200	13,023,667.00	26,431,702.00	1%

As graphically underlined, the system sized with the *VE Sizing&Pricing* tool in *HOMER* is the best system that meets the customer needs with less than the 10% of LLP. This does not mean that Village Energy systems are all sized to meet the 90% of the load because the context-based intuitive method at the basis of the *VE Sizing&Pricing* tool leads to rounding-off the size of each component. However, the results of HOMER are useful to conclude that, in order to satisfy more loads, there is no need for more power from the PV but there is the necessity to increase the installed capacity to compensate even the cloudy days.

3.3.3 Comparison between *VE Sizing&Pricing* tool and *HOMER*

HOMER is definitely a more sophisticated instrument if compared to the *VE Sizing&Pricing* tool. The ability to simulate the real behaviour of the system hour by hour will certainly make it more complete and accurate. However, the inputs required by the software make it inappropriate for a real context such as the one experienced by the author in Village Energy. Indeed, some aspects of *HOMER* pose serious limits to its adaptability and flexibility:

- The necessity to wait for simulation results: since HOMER simulates every PV-battery combinations, time is required to have results. This aspect, especially if the hardware availability is scarce, can lead to a non-immediate satisfaction of the client's needs.
- The impossibility of size the system without fixing an LLP: in contexts such as the one in consideration is not realistic to think that the clients knows which is the maximum load that he does not want to be satisfied. It is also difficult to explain to the customer that to a smaller LLP requested corresponds a higher investment cost. The employee is therefore legitimated to expect trivial answer as the will of a load totally satisfied. From the user side the problem persists because the choice of this parameter affects the results list and there is no clear match between the needs of the customer and the calculation of a hypothetical LLP. What should be the questions to the client in order to detect this parameter: how much is the customer willing to accept a non-functioning device?
- The inability to find the best system without calculating the NPC: since *HOMER* orders the systems that respect the maximum LLP and choses the one that presents the minimum NPC, the calculation of the Net Present Cost is required. This fact differs from what resulting from the *VE Sizing&Pricing* tool which, to date, provides only the cost of investment with additional information regarding the possibility of batteries' replacement over the years. The non-adaptability can be found in such aspect because the client is interested only in the investment cost

because the uncertainty of the future mentioned above makes him not available to think about future costs. Thus, the user has two solutions: or set the software to calculate an unrealistic NPC on an investment period of 1 year to obtain the coincidence with the investment cost, or manually reorder the results based on the investment cost. Moreover to calculate NPC, information regard maintenance and replacement of each components joined with economical assumption such as the real interest rate (a parameter that is difficult to determine and not very stable over the years in underdeveloped contexts) in order to actualize the future cash flow, should be estimated and insert in the software.

- The necessity to have too precise load information: indeed, *HOMER* requires the hourly load profile, but this information cannot be obtained directly from the customer, who already finds it difficult to make a differentiation between daily and night load as required in the *VE Sizing&Pricing* tool. The employee who uses *HOMER* instead of *VE Sizing&Pricing* should estimate the distribution of loads in the various hours of the day.
- The impossibility to set up the DC bus voltage: this shortcoming impacts on the fact that the user must, in each case under consideration, reinsert the list of sizes of PV array to be simulated in such a way that the power under particular simulation emerges from the sum of powers of at least the number of modules that returns the right DC voltage. Thus, the user must keep aside, probably on a Microsoft Office excel sheet, an updated list of modules available on the market, and combine this list in order to obtain the correct sizes of PV array to be inserted in *HOMER*.
- The difficulty to test simultaneously different types of battery with different capacities: in *HOMER* to simulate different capacities, the user must choose a battery type and vary the number, so the step of simulated capacity is decided by the size of the particular type of battery chosen. The problem is that in the case of Village Energy, batteries' selection is based on a database not necessarily composed by a combination of a single battery (Table B.0.1). Only assuming that more than one battery is effectively connected to the PV array (Fig 3.7) it is possible to take into account the real database also in *HOMER*. However, 10 batteries at maximum can be connected simultaneously in the same system so if the database has more than 10 different types of batteries the user must choose the 10 he wants to simulate. Moreover, also in this case, the user must keep aside an updated list of batteries available on the market, and combine this list in order to obtain the number of batteries among the same type to be inserted in *HOMER.*
- The lack of charge controllers' sizing information: *HOMER* does not size the charge controller for the user. The employee who uses *HOMER* instead of *VE Sizing&Pricing* tool should estimate the size of these components by himself. Moreover, there is no space where taking into account the cost of this component but such cost must be added manually by including it in the cost of the PV array. Therefore, once again, the user needs to update a database of such component aside, and consider it when he comes to deciding which sizes of PV arrays to simulate in the particular case under consideration.
- The impossibility to consider others variable costs: despite being aware that *HOMER* was not thought to take into account the cost of those components needed for the system's installation, however, it remains to point out that completely lacks a space to add additional costs that may vary according to the size of others component. Installation costs can be kept into consideration as fixed costs, which are the same for all simulated system even though this does not correspond to reality because, for example, different section of the cables are needed in case of different sizes of PV array.

- The inability to make a quotation for the client: the user should elaborate again apart the cost outputs from *HOMER* to get a final price for the customer that takes into account also administration fees, commission and the business strategies of the company in terms of profit percentage.

For all these reasons it is possible to conclude that *HOMER*, despite being a valid tool for simulation, does not respond to the characteristics asked by the company and listed in Section 3.1. On the contrary, the *VE Sizing&Pricing* tool it appears to be more appropriate for the necessity of a solar company like Village Energy Uganda Ltd. Indeed it is:

1. *Simple but accurate*: it requires some inputs from costumer and automatically guides the user towards the compilation of the quotation to be printed for the client. Based on intuitive methods, it provides sizing results that have been validate in terms of accuracy with those obtained with *HOMER.*
2. *Fast*: being designed to operate automatically by taking advantage from information already pre-set, it permits to the user to generate a quote in few minutes;
3. *Flexible*: the numerous cells that can be changed in each Microsoft Excel sheet of which is composed by, make it able to adapt to any particular request of the client;
4. *Market-based*: it presents a detailed database that stores all the components used by the company in its installation. Thus, the final results are adapted to the particular context, in terms of components that actually exist on the market;
5. *Editable in the future*: the database, the sizing approach and the economic assumptions can be changed whenever it needs.

Chapter 4

4. Sizing of PV Micro-Grid: an Appropriate Numerical Method for Developing Countries

The main objective of this chapter is to present the investigation on the PV Micro-Grid sizing matter. After a brief introduction that explains the motivations of the work, the numerical model implemented in MATLAB® is exposed, highlighting the new features introduced in order to develop an appropriate numerical Micro-Grid sizing method for real-context based application in developing countries. Finally, a case of study based on the Ugandan context is chosen and a results' comparison with those computed using intuitive method and the software *HOMER* is proposed.

4.1 Motivations

It is possible to summarize the motivations that have leaded the investigation on the matter of PV Micro-Grid in three principal aspects:

1. The interest in investigating the pro & con of numerical methods for the design of "Off-Main-Grid" Photovoltaic systems. These methods, although applicable to any size of plant, acquire greater value on case studies of particular relevance, which can be for example a PV Micro-Grid, because the ability to simulate the real behaviour of the plant can make a difference on the sizing results. Indeed, it was shown in Chap.3 that on small sizes, typical of the SAPV systems, a sizing tool based on intuitive method might be more practical and appropriate if compared to sophisticated numerical-based software like *HOMER*, when placed in the context of the real usage of a company active in photovoltaic installations. Thus, the focus has been precisely to verify the possibility of making even numerical methods appropriate to the real contexts.
2. PV Micro-Grids represent a valid alternative for rural or peri-urban electrification to the SAPV system. Assuming for example a rural village composed by 100 households, the same results in terms of electrification can be obtain with 100 SAPV home based systems installed on each roof or with a unique centralized photovoltaic Micro-Grid connected to each of the 100 users. The benefits of the

second solution are in terms of reliability (the maintenance and problems are concentrated in a single zone) and total costs being able to take advantage of economies of scale. Moreover, while SAPV systems, being of small size, can hardly be taken into consideration in developing countries' energy planning, but can at the maximum benefit from incentives by national institutions, the PV Micro-Grids, having the aim of reach a significant number of users, may instead benefit from higher attention by the central authorities who can evaluate the possibility of installing such systems to compensate the lack of spread of the national grid.

3. The strong interest in the scientific research about Micro-Grids matter, especially in terms of sizing approach, planning, simulation and control. Micro-Grids, which address several consumers providing centralized electricity generation at the local level using a village distribution network, can be based on:
    - Renewables: ranging from grids relying on a single source to micro-grids that can integrate more than one source of energy (hydro, biomass, wind and solar), they are characterized by an high investment and a low O&M costs being “fuel free”. The negative points are the strongly dependence on batteries to avoid blackouts and the not dispatchability of the produced energy.
    - Diesel Generators: characterized by a lower capital investment and higher O&M costs if compared with the renewables solution, permit to give electricity when necessary but with the compromise of the noise and pollution they cause.
    - Hybrid Solutions: relying on renewable energy to generate most of the total supply, they present a genset as a backup in order to reduce the battery size. These options take the positive aspects of the previous configurations to give an optimized solution in terms of costs and quality of service.

   In the framework of "Off-Main-Grid" Photovoltaic systems solutions, the PV Micro-Grid, based only on photovoltaic source with additional battery storage, have been chosen as the subject of this chapter to contextualize such a solution in developing countries with particular reference to the case of Uganda.

In this framework, the physical operation of a PV Micro-Grid has been simulated by developing a MATLAB® code based on numerical methods. As stressed in Chap. 2, the discriminant to obtain more precise results in this methods is to have accurate physical models that best describe each system component (i.e. PV array, battery bank, inverters, etc.). However, having clear the main objective, which is to focalize the attention on the appropriateness of the sizing method, the physical model has been developed starting from an ideal description and introducing more detailed components model gradually according to the most established scientific-literature based models. Obviously, a future development of the proposed model is to improve the modelling of system components (especially the battery model). Finally, the “appropriateness” feature of the proposed model is in the criterion (i.e. the objective function) that the numerical method uses to choose the best combination of components that addresses the load.

4.2 Numerical model in MATLAB®

The first step has been to develop the simulator in order to be able to compare different systems, (i.e. different combinations of panels and batteries). Based on the scientific literature on the numerical methods, explained in Section 2.3.2, it has been possible to build up a simulation model in MATLAB® which takes into account all the main aspects which characterize a PV Micro-Grid.

4.2.1 Physical modelling

In developing the numerical model only the components that form the system: PV array, battery bank and the inverter, have been taken into consideration. With reference to Fig 2.12 only AC loads have been considered assuming that the calculation of the load must be take into account also losses on the transmission system.

In the next paragraphs, the main aspects, which have been implemented in MATLAB® such the load curve, the solar resource and all the component's descriptions, are presented. Note that plant simulations have been done progressively introducing efficiencies and component's models that try to take into account the real behaviour of the system, these aspects are presented in the next paragraphs highlighting the differences that exist between an *ideal model*, and a *final model* (i.e. with real components models).

Load curve

The load estimation is a prerequisite to obtain any results from any sizing method. In numerical models the time-step details of the load must be consistent with the simulation step to be used. If the simulation is set on hourly time-step, coherent information needs to be grouped for each appliance that has to be powered by the PV Micro-Grid. In order to create the load curve shown in Fig 4.1, basic data regarding the appliances such as power and number of the appliance *ith* and hours of functioning (h_{funct}) of each devices *ith* used by the costumer, need to be collected as shown in Table 4.1. Then, following the typical literature's approach, *windows of utilization* have been defined in number and duration as the specific operating time range during which the device *ith* is normally switched on. These windows define the number of possible hours of utilization (h_W) of the device *ith* and consequently also the distribution of energy consumption over the day. For example, referring to the sample showed in the table, the energy demand of the fridge, which is of 1500 Wh resulting from a power of 250 W that runs for 6 hours of functioning, are distributed on the 24 hours (i.e. the window of utilization defined by the user) of the day giving as results a constant energy consumption of about 53 Wh over the day. Obviously, this calculation permits to preserve the energetic demand of the device *ith* during the specific hour, but not the power demand which is not of 53 W for an entire hour, in fact the same example can be read in the way that the fridge works for 12.5 minutes for each hours of the day at the rated power consumption. However, having recognised this limitation in literature, the same method has been used by the author, leaving as further development the investigation of solution, which could be the passage from hourly-based simulation to the minute time-step in order to better describe the real behaviour of the *ith* device.

Having obtained the load curve, the same load profile has been replicated for all the day of the years. Neither the seasonal variability, neither the midweek variability between work days and week-end have been considered, because, the main objective of

Table 4.1 Sample of appliances information for hourly-based numerical model.

APPLIANCE	**Power [W]**	**N°$_{App}$**	**h_{funct}**	**N°$_{Win}$**	**W_1**		**W_2**		**W_3**		**h_w**
Lights (normal)	3	8	6	2	0	2	17	24	-	-	9
Phone Charger	5	2	3	3	0	9	13	15	17	24	18
Security Light	5	2	12	2	0	7	17	24	-	-	14
TV 20”	100	1	5	2	11	15	17	24	-	-	11
Fridge	250	1	5	1	0	24	-	-	-	-	24

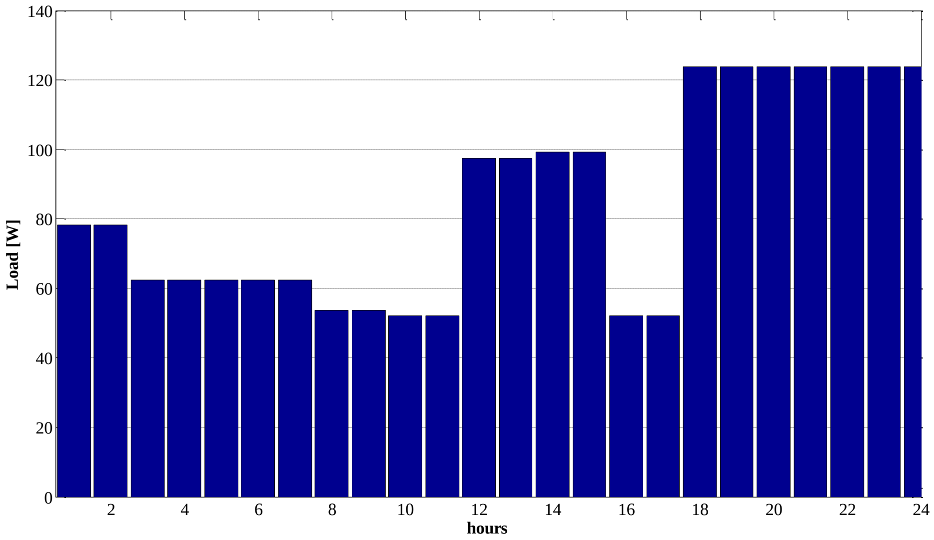


Fig 4.1 Sample of load curve for hourly-based numerical model.

the analysis is the appropriateness of the sizing method, and it has been deliberately decided to leave the investigation of load curve matter to further studies. In this way, it has been possible to create the yearly array of load to be put in the MATLAB® model and compared with the array of yearly energy produced by the system.

Solar resource

The solar resource profile over the year is needed in the numerical model because at the basis of the PV array energy output calculation. In particular, what required is the incident radiation on tilted surface. Some algorithms are available in scientific literature to generate synthetic hourly global solar radiation data. For the scope of this work, it has been decided to rely on the HDKR model on which is based the algorithm [73] implemented in *HOMER*, which, starting from the mean daily solar radiation values for every month (available from different sources like [66]), calculates the global solar radiation incident on the surface of the PV array for a given tilt angle and for each time-step. Thus, imposing the latitude and longitude of the place as well as the tilt of the modules, it has been possible to obtain automatically the hourly array of the incident radiation on tilted surface over the year.

Similarly, since the PV cell temperature is needed for the calculation of the PV array energy output, it has been taken from *HOMER* that, starting from mean daily temperature values for every month, rebuilds the temperature profile and calculates the cell temperature in each time step over the year based on equation of [74].

An example of what has been mentioned is shown in Fig 4.2 for the location of Soroti in Uganda (1.72N / 33.6E). The incident radiation on tilted surface and consequently the irradiation value, which is represented by the yellow area, are exposed in the upper part of the figure for the first five days of the year. Note that, since HOMER takes (randomly) into account the presence of cloudy days over the year, which is evident for three of the five days showed in the figure, this aspects is considered also in the MATLAB® model. Coherently, the cell temperature profile is exposed in the lower part of the figure; during the night the cell temperature is the same as the ambient temperature, but in full sun the cell temperature can exceed the ambient temperature by 30°C or more.

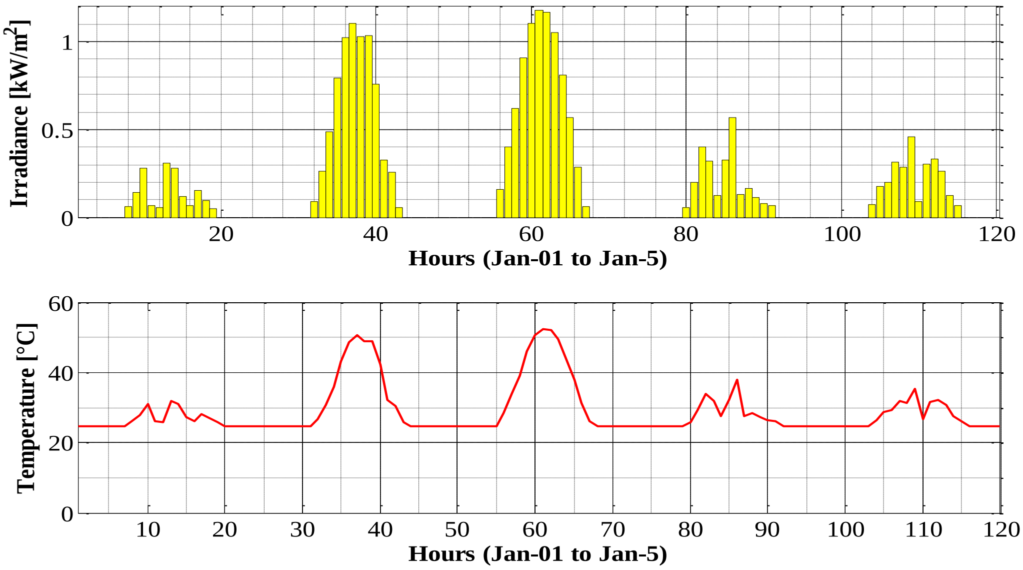


Fig 4.2 Sample of incident solar radiation and cell temperature data taken from *HOMER.*

Inverter

The inverter power has been sized on the maximum power required by the load taking into account the inverter efficiency as follows:

$$P_{Inv} = \frac{P_{L,max}}{\eta_{Inv}} \tag{4.1}$$

The inverter efficiency (η_{Inv}) has been set equal to 100% in the ideal simulation and, more realistically, equal to 90% in the final simulation.

Once again, it is need to point out that sizing the inverter on the maximum of the load curve, obtained as described previously, which does not take into account the maximum power requirements of the devices can lead to underestimate the power of the inverter.

PV array

Since the MATLAB® model simulates systems composed by different size of the PV array, for all of these systems the estimation of PV energy output array is required. For each time-step (t) of the year the equation is the following:

$$E_{PV}(t) = P_{PV}\,\frac{\mathrm{H}_{\beta}(t)}{h}\,\eta_{BOS} \tag{4.2}$$

Where, $H_{\beta}(t)$ is the specific solar irradiation on tilted surface value as shown in Fig 4.2 for the chosen time-step, P_{PV} is the rated power (kW) of the PV array under simulation at standard test condition which are an irradiance h of 1 kW/m^2, an ambient temperature of 25 °C and an air mass value of 1,5.

Regarding the BOS efficiency, it has been set equal to 100% in the ideal simulation and, more realistically, equal to 85% in the final simulation taking into account all the losses not related directly to the sun energy conversion process, such as:

- Power losses: which arise when there are deviations from standard test conditions and the actual working conditions of a photovoltaic module.

- Losses due to reflection: generated by the percentage of the light radiation that is reflected by the glass placed at protection of the cells.
- Losses due to mismatching: caused by the series connection of PV modules that is not perfectly identical.
- Losses along the DC bus: caused by the resistance of the power line.
- Losses due to dirt and dust: which depend on the installation site, the weather conditions and the inclination of the modules.

As a further step, the solar cell temperature has been taken into consideration as affects the output of the photovoltaic modules. Based on data of cell temperature (T_{Cell}) as explained in Fig 4.2, Equation (4.2) has been corrected as follows:

$$E_{PV}(t) = P_{PV}\left(1 - \rho_T\left(T_{Cell}(t) - T_{Rif}\right)\right)\frac{\mathrm{H}_{\beta}(t)}{h}\,\eta_{BOS} \tag{4.3}$$

With ρ the negative temperature coefficient of power respect to solar cell temperature set to the value of 0.4 %/°C and T_{Rif} the temperature at test condition set to the value of 25 °C.

Battery bank

The next step has been to describe the battery bank behaviour estimating the amount of energy that flows through the battery and the change in the battery state of charge. The battery model that has been chosen is the simplest battery model that can be implemented within numerical methods and literature refers to it as ideal battery model. Indeed, it describes the battery bank as a perfect storage of energy $E_{Bat,rated}$.

For each time-step the difference between PV array output ($E_{PV}(t)$) and load required by the user ($E_L(t)$) after inverter efficiency has been calculated as follows:

$$\Delta E = E_{PV}(t) - \frac{E_L(t)}{\eta_{Inv}} \tag{4.4}$$

Clearly, if the difference is positive the battery will be under charge, on the contrary a discharge will occur.

$$E_{Bat}(t) = \begin{cases} \Delta E\,\eta_{Bat,CH}\ , & \Delta E > 0 \\ \dfrac{\Delta E}{\eta_{Bat,DISCH}}\ , & \Delta E < 0 \end{cases} \tag{4.5}$$

Where $\eta_{Bat,CH}$ and $\eta_{Bat,DISCH}$ are respectively the battery charge and discharge efficiencies which both has been set equal to 100% in the ideal simulation and, more realistically, equal respectively to 85% and 90% in the final simulation. In both cases, the battery state of charge needs to be updated based on the amount previously stored value.

$$SOC(t) = SOC(t-1) \pm \frac{E_{Bat}(t)}{E_{Bat,rated}} \tag{4.6}$$

Furthermore, the energy stored in the battery is subjected to the following constraints:

- The respect of a minimum (SOC_{min}) and maximum (SOC_{max}) level of the state of charge, which have been set respectively to the value of 40% and 100%. Clearly, the controller, the work of which, in installations of a certain size, it is done by a single power conditioning unit (PCU) comprising also the inverter (as shown in Fig 2.12), is the component that monitors the battery *SOC*.

– The respect of the power-energy ratio ($(P/E)_R$) of the battery: in fact a battery of energy $E_{Bat,rated}$ it cannot accept or provide every amount of inflow or outflow energy. There is a limit that have been set to 0.5, so if the battery rated capacity is of 1 kWh, this means that it can at maximum provide or accept 500W for an entire hour.

Regarding the battery lifetime two approaches have been implemented both of which have been explained in Section 2.3.2. The first one is the equivalent full cycles to failure method, used in the ideal simulation, which defines the end of a battery lifetime when the energy taken or added from the battery has reached the maximum value of energy that can be taken or added from the battery during a specified number of full charge-discharge cycles (set arbitrarily to the value of 2000). The second one is the "rainflow" cycles counting method, used in the final simulation, which consists on counting the charge/discharge cycles corresponding to each range of the DOD for a year, based on Fig 2.7, to be used in Equation (2.38).

4.2.2 Simulation

Once described all the above aspects in MATLAB®, the objective has been to simulate different combination of PV array and battery bank in order to have results to choose the best one. First of all, two simulations settings are common for all the analyses:

- Time-step: an hourly-based simulation has been chosen especially for the chance to have shorter computational time, leaving to further development the investigation towards the use of a tighter time-step like the minute, which makes available a better description of load and components. Each system is simulated over one year, which is taken as reference meaning that the results are assumed valid also for the next year of operation.
- Simulation-range: it has been decided that it should remain independent from the reality of the components available on the market, thus, for example, a simulated plant of 148 kW does not mean that such a system can actually be realized but remains the responsibility of the installer to verify the feasibility on the site, subject to the combination of different modules such that they reach the recommended power. This is true for all main components: modules, batteries and inverter. With this assumption, the simulation-step for PV array has been set on the value of 1 kW while the simulation-step for the battery bank has been set to the value of 5 kWh.

Description of the System operation

Before being able to calculate and compare simulation results, some parameters have been considered to describe the operation of PV Micro-Grid: the Loss of Photovoltaic energy (*LPV*), the Useful Photovoltaic energy (*UPV*) and the Loss of Load (*LL*).

The LPV represents the amount of energy available from the PV array ($E_{PV}(t)$) that is not exploited by the system because the battery is not able to receive it. Thus, it is computed during the charge phase ($\Delta E > 0$) when two specific conditions are verified:

$$\mathrm{LPV}(t) = \begin{cases} \dfrac{SOC(t) - SOC_{max}}{\eta_{Bat,CH}} E_{Bat,rated} \,, & SOC(t) > SOC_{max} \\ \Delta E - (P/E)_R \, E_{Bat,rated} \, \Delta t \,, & \dfrac{\Delta E}{\Delta t} \geq (P/E)_R \, E_{Bat,rated} \end{cases} \tag{4.7}$$

From the LPV it is also possible to calculate the UPV, which represents the energy produced and affectively used by the PV array:

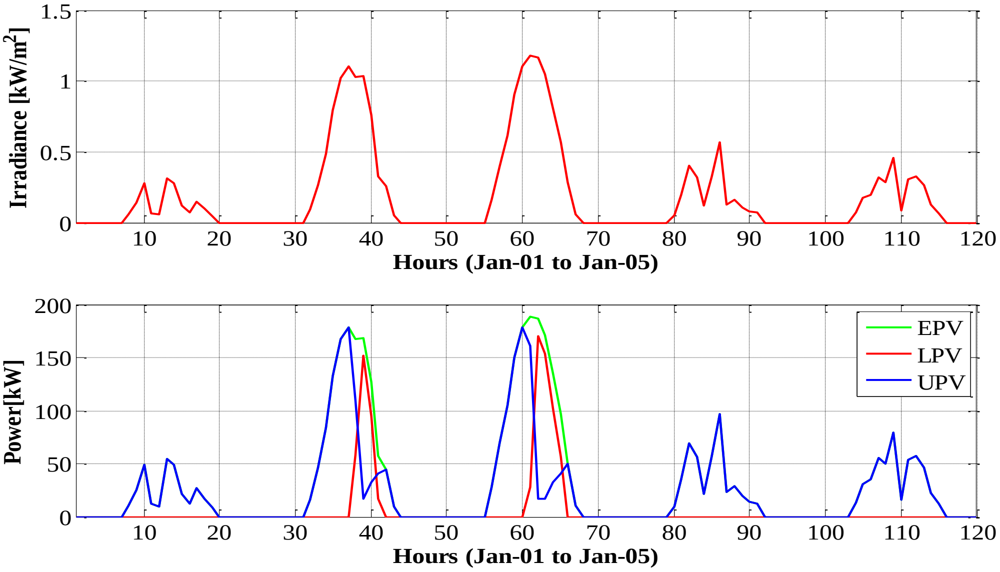


Fig 4.3 Incident solar radiation and PV array output.

$$UPV(t) = E_{PV}(t) - \mathrm{LPV}(t) \tag{4.8}$$

In Fig 4.3 the trend of the cited parameters for the first five days of the year for a PV array of 200 kW is exposed. The PV energy output (E_{PV}(t)) is represented by the area limited by the green line and it is strongly related to the incident radiation on tilted surface exposed in the upper part of the figure. However, because of the limitations imposed in Equation (4.7), part of this energy cannot be exploited by the battery bank. Thus, as highlighted by the red line, the LPV emerges principally at the end of a sunny day when the battery bank reaches the fully charged state and no other energy can be accepted. The result is the UPV, showed in the area limited by the blue line, which represents the photovoltaic energy really produced by the PV array.

Regarding the LL indicator, it represents the amount of energy required by the load that remains unsatisfied from the system because the battery is not able to provide it. Thus, it is computed during the discharge phase ($\Delta E < 0$) when two specific conditions are verified:

$$\mathrm{LL}(t) = \begin{cases} (SOC_{min} - SOC(t))\, \eta_{Bat,DISCH}\ \eta_{INV}\ E_{Bat,rated}\ , & SOC(t) < SOC_{min} \\ (\Delta E - (\mathrm{P/E})_R\ E_{Bat,rated}\ \Delta t)\ \eta_{INV}\ , & \dfrac{\Delta E}{\Delta t} \geq (\mathrm{P/E})_R\ E_{Bat,rated} \end{cases} \tag{4.9}$$

In Fig 4.4 an example on how the MATLAB® model works is exposed. The unmet load is represented by the red line. Note that the area under such line returns exactly the LL calculated in Equation (4.9). The unsatisfied load occurs principally after poor days of insolation when the PV array energy output (represented by the magenta line) has not been able to fully charge the battery. This is underlined by the SOC trend (blue line) which does not reach the 100% as happens after the two sunny days. This fact causes that the battery bank discharges rapidly during the first hours of the night and it reaches the minimum SOC allowable for which the battery can no longer provide energy, leaving the next load not covered. In the same figure is possible to stress again the fact that the PV array energy output is deeply linked with the battery SOC. In fact, when the battery SOC reaches the 100% the PV production decreases, continuing to cover the load (represented by the green line) because the battery is fully charged.

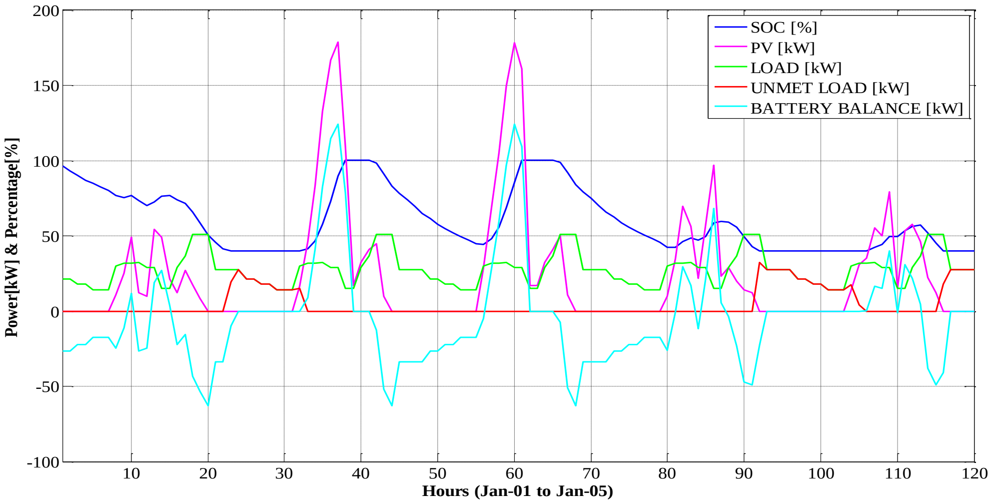


Fig 4.4 Sample description of system operation.

Finally, with the cyan colour, is represented the inflow or outflow energy through the battery bank. Obviously, the battery bank follows closely the trend of the PV array energy output during the daily hours having to recharge, and it follows the trend of the load during the night hours being delegated primarily to cover the night energy demand.

Monitored performance parameters

The analysis and comparison among different simulated systems has been done based on common assumptions. In the next lines, simulation results are exposed for a simulated field that goes from 100 kW to 200 kW for PV array power and from 500 kWh to 1500 kWh for the battery bank, having imposed the total daily load calculated by the author for a typical rural agglomerated of 100 households and other business activities in Soroti (Uganda), a real context that is exposed in the following case of study.

The monitored performance parameters are the Loss of Load Probability (*LLP*), the Loss of Photovoltaic energy Probability (*LPVP*) and the Net Present Cost (*NPC*).

The LLP, as known from previous sections, describes the reliability of power supply to load [48]. Its definition is the percentage of the total load required by the user that remains not satisfied and can be mathematically defined as:

$$LLP = \frac{\sum_{t=1}^{8760} \mathrm{LL}(t)}{E_{L,year}} \tag{4.10}$$

In Fig 4.5 the LLP results for the simulated systems are exposed. As it may seem obvious the LLP value is higher for systems with undersized components and tending to zero value for oversized systems.

The LPVP describes the percentage of the PV array producible energy that is not exploited by the system and can be mathematically defined as:

$$LPVP = \frac{\sum_{t=1}^{8760} LPV(t)}{\sum_{t=1}^{8760} E_{PV}(t)} \tag{4.11}$$

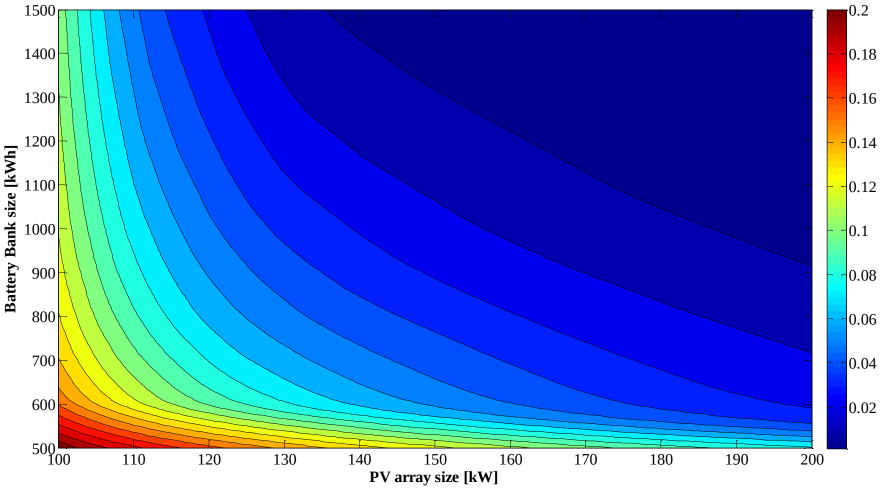


Fig 4.5 LLP results for sample simulated systems.

In Fig 4.6 the LPVP results for the simulated systems are exposed. As appears evident, to systems with an oversized battery bank benefit of a less LPVP since they can stock more energy in the storage. On the contrary having an high installed power of PV array it is not necessary equivalent to having more energy available for the load if this system is not associated with a battery of the correct size. Indeed, such system can probably cover all the daily load but, without the right storage capacity that can receive the energy coming from the PV array, it will not be able to exploit the excess energy to make it available during the night.

The last parameter computed is the Net Present Value (*NPC*). The system life cycle has been set on 20 years as the life cycle of the PV array. The yearly cash flows, which are principally due to operation and maintenance costs ($c_{O\&M}$), specific to the size of the PV array, and the component's replacement, have been actualized assuming a real interest rate r of 6%. Regarding the cost of components, specific cost that can be collected on the field as done by the author for the case of Uganda, has been assumed. Thus, the NPC can be calculated as follows:

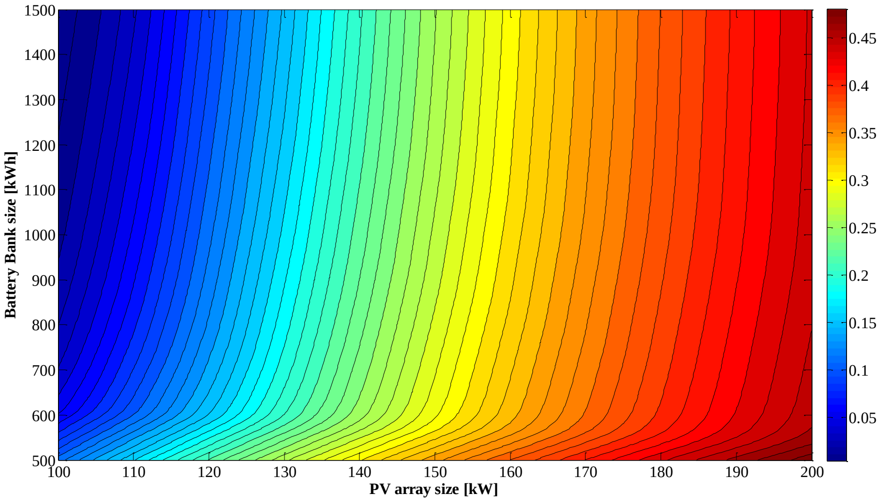


Fig 4.6 LPVP results for sample simulated systems.

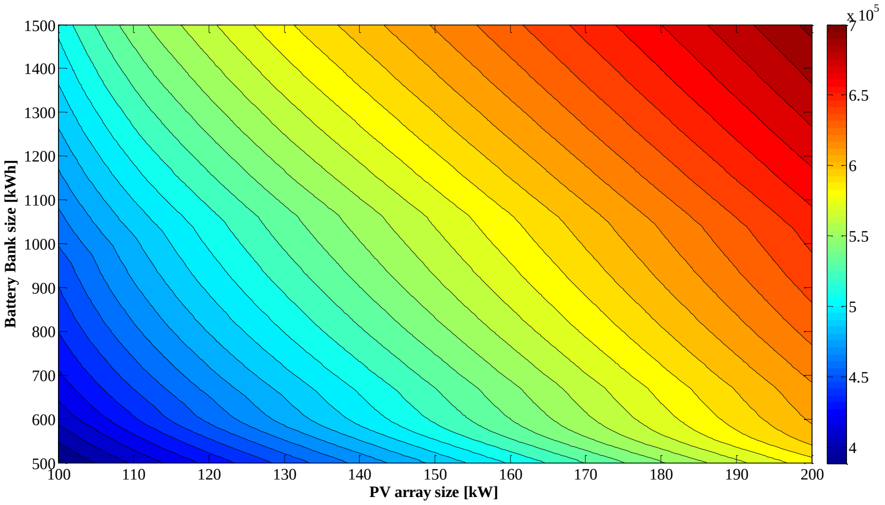


Fig 4.7 NPC results for sample simulated systems [€].

$$NPC = C_{Inv} + \sum_{i=1}^{20} \frac{P_{PV} c_{O\&M,i} + E_{Bat} c_{Rep,Bat,i} + E_{L,max} c_{Rep,Inv,i}}{(1+r)^i} \tag{4.12}$$

Note that among the component's replacement, the batteries substitution is certainly the most relevant. The life cycle of the battery bank has been calculated as previously explained and considered in the calculation of the correspondent cash flows in Equation (4.12). Regarding the inverter, an assumption of a single replacement when reaching the middle of the system life cycle has been done by the author. Concerning the cost of investments (C_{Inv}) is calculated as follows:

$$C_{Inv} = P_{PV} c_{PV} + E_{Bat} c_{Bat} + E_{L,max} c_{Inv} + C_{Others} \tag{4.13}$$

Where the cost of others has been set as the 20% of the sum of the previous investment costs and includes installation, design and others components costs like wire and connections.

In Fig 4.7 the NPC results in € for the simulated systems are exposed. As might be expected, the costs are higher for those systems with larger components. Note that, as the exposed results are referred to systems in which the equivalent full cycles to failure method for the determination of battery's life cylce is implemented, a more accurate determination of this aspect, such as the "rainflow" cycles counting method, have a strong impact on the NPC since systems with a smaller installed battery bank requires more substitutions over years with consequences on future cash flows.

4.2.3 Optimization: an appropriate new approach

As stressed before, in the numerical methods different systems (i.e. different combinations of panels and batteries) are simulated and a common criterion is used to choose the best combination that addresses the load.

The classic approach that can be found in literature consists in matching the load demand under a specific LLP, fixed by the designer, at the minimum NPC over the life cycle of the system [48]. A description of this approach can be given by mean of Fig 4.8 which represents the results of a generic simulation. Looking at the graph, it can be noticed that different size combinations of solar array and battery can meet the given load demand for the desired LLP (the green lines). However, looking at the cyan lines, which represent values of NPC, there is only one combination of PV array and battery bank for a specific LLP (showed with the triangular blue marker) that presents the minimum NPC and it occurs precisely at the point where the NPC curve is tangent to the LLP curve. For example, if the designer decides that the PV Micro-Grid must provide energy with a final load satisfaction of the 90%, from this figure it is possible to read that for the corresponding LLP value of the 10% the best system to be installed is the one presenting a PV array of about 125 kW and a Battery Bank of about 800 kWh, because it is the system that presents the minimum NPC being tangent with the constant curve of about 600’000 €.

However, three are the main limitations of this approach that have been recognised when referring to real context in un-electrified areas of developing countries:

1. The impossibility to define the LLP: as already mentioned in Chap. 3, it is not realistic to think that the designer or the customer reached by the PV Micro-grid know which is the maximum load that can be lost. Moreover, in any case, the targeted LLP value cannot be defined *a-priori* and a further analysis is required to set properly the LLP. An example could be the case of a PV Micro-Grid that serves a rural village that has never had electricity before. What should be the correct LLP? What is the analysis to be accomplished to set the LLP?
2. The Net Present Cost does not take into account all the cost over the life cycle of the PV Micro-Grid: referring to the case previously cited, it is possible to imagine that the households living in such village have made use of different solutions before having electricity from the PV Micro-Grid (e.g. kerosene lamps, small diesel gensets, batteries, etc.) in order to have lights during night. Thus, if the PV Micro-Grid leaves uncovered some loads during the years as expressed by the percentage of LLP, this means that people may return to previous system to have light during the hours not satisfied, spending more money not included in the calculation of the NPC as above, but that really concern it, because they represent a lack of the system to be economically calculated.

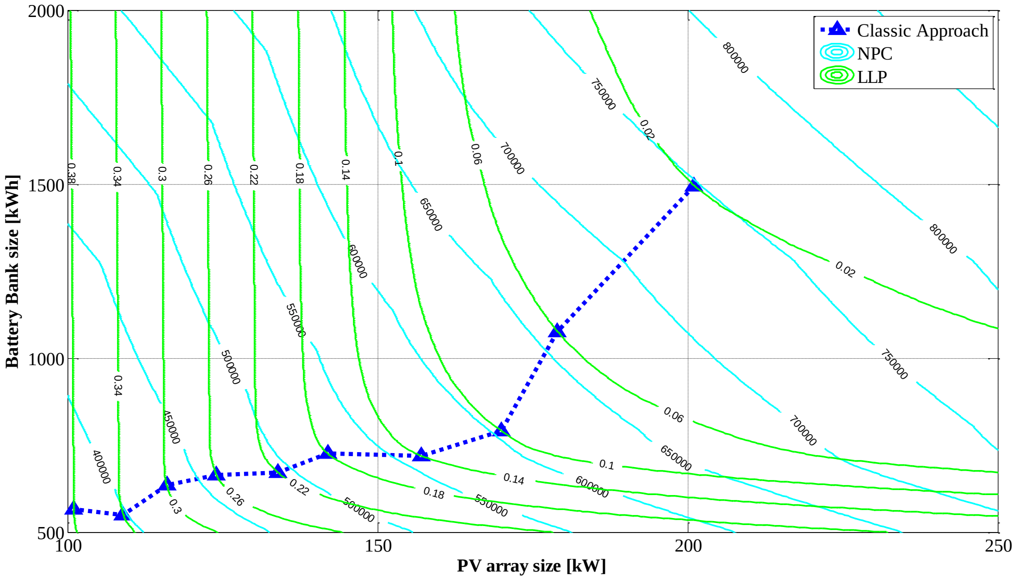


Fig 4.8 Classic approach of optimization.

3. The optimization phase is in two steps: the designer has to find all the systems that address the load with the fixed LLP value and order the corresponding NPC of the same systems in a second step to find the one with the minimum value.

The objective function

Having recognised and exposed the limitations, the main feature of the new approach has been to set an economical value for the load not satisfied (LL_{value}) by the PV Micro-Grid. In this perspective, the LL cumulated during the simulated year of operation is a new negative cash flow to be computed in order to obtain a modified NPC of the PV Micro-Grid installed. Thus, Equation (4.12) becomes:

$$NPC_{mod} = C_{Inv} + \sum_{i=1}^{20} \frac{CF_i + (\sum_{t=1}^{8760} \mathrm{LL}(t)) \cdot LL_{value}}{(1+r)^i} \tag{4.14}$$

Note that the results over one year of simulation are assumed valid also for the next year of operation, so the LL cumulated appearing in the numerator in Equation (4.14) remains the same for all the life cycle of the system.

In Fig 4.9 the modified NPC results for the simulated systems with a valorization of the load unsatisfied set to 0.30 €/kWh are exposed. As showed graphically, since the new term in the numerators introduces negative cash flows for those systems which are undersized, a area of minimum is emerging. However this does not mean that it is possibile to use the modified NPC to find the best system, because this would be to choose the minimum based only on economic criteria without taking into account the satisfaction of the load. Indeed, also the classic approach, first looks at the satisfaction of the load setting the LLP, and only after this step it looks at the NPC.

Moreover, beside the necessity to add a factor that takes into account the satisfaction of the client’s needs, the other aim has been to make the MATLAB® model able to determine the best system in one step.

In this direction, the choice has been to use the Levelized Cost of Energy (LCOE) with reference to the IEA definition [77] appropriately modified for the context under consideration.

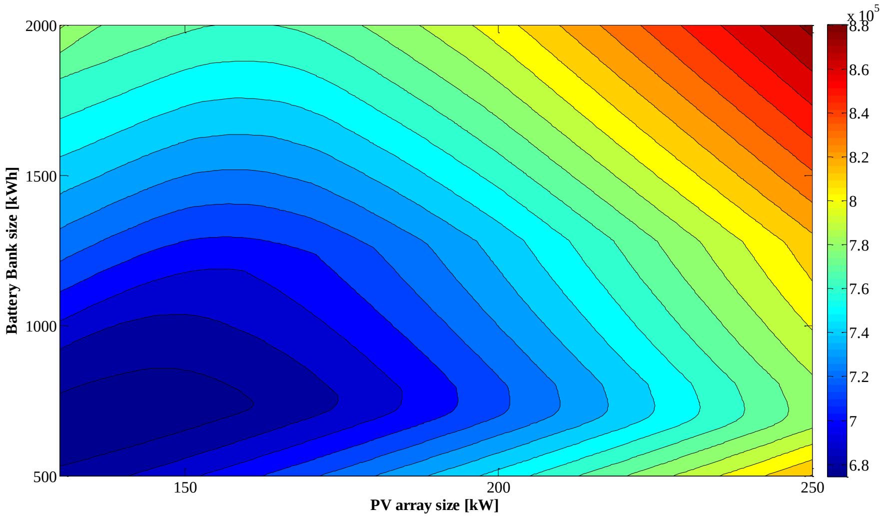


Fig 4.9 Modified NPC results for sample simulated systems [€].

The calculation of the LCOE derives from the equality between the present value of the sum of discounted revenues (*NPR*) and the present value of the sum of discounted costs, which is equal to the NPC calculated in Equation (4.12).

$$NPR = \sum_{i=1}^{20} \frac{EE_i \cdot p_{EE}}{(1+r)^i} = NPC \tag{4.15}$$

Whit EE_i the amount of electricity produced by the PV array during the *ith* year and p_{EE} the constant price of electricity. Thus, the LCOE is given by:

$$LCOE = p_{EE} = \frac{NPC}{\sum_{i=1}^{20} \frac{EE_i}{(1+r)^i}} \tag{4.16}$$

Taking into account the real cost over the life cycle and recognising that in an "Off-Main-Grid" technology the electricity produced by the system is the one that really reaches the load, the LCOE has been modified by introducing the new NPC (Equation (4.14)) and the satisfied load as follows:

$$f_{obj} = LCOE_{mod} = \frac{NPC_{mod}}{\sum_{i=1}^{20} \frac{E_L(1-LLP)}{(1+r)^i}} \tag{4.17}$$

The choice of this objective function turns out to be appropriate because it presents both the fundamental elements mentioned above. In fact, at the numerator, the NPC_{mod} plays the role of economical parameter, while the denominator represents the factor of customer's satisfaction as it expresses how much of the load required by the customer is actually satisfied.

In Fig 4.10 the results of the objective function as a modified LCOE in €/kWh for the simulated systems with a valorization of the load unsatisfied set to 0.30 €/kWh are exposed. As appears clearly such function presents a minimum that, in the specific simulation, is of about 0.272 €/kWh for a system with a a PV array of 180 kW and a battery bank of 980 kWh which is able to guarantee an LLP of 6.53%.

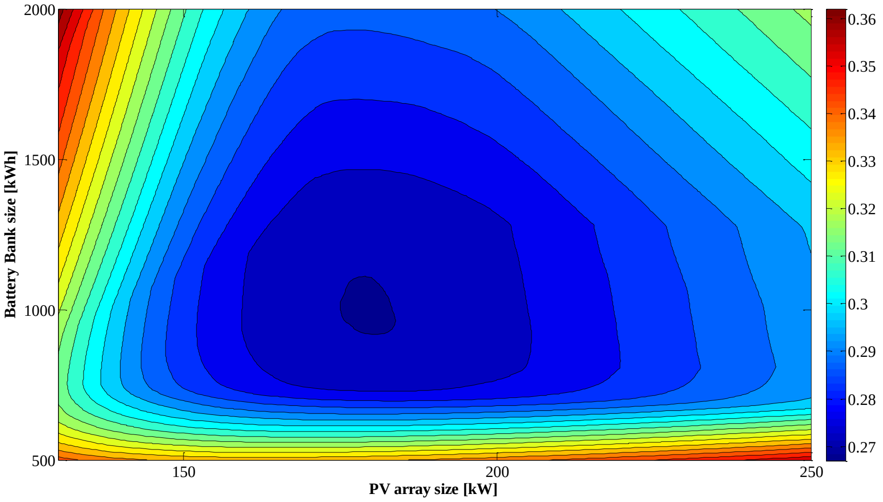


Fig 4.10 Objective function results for sample simulated systems [€/kWh].

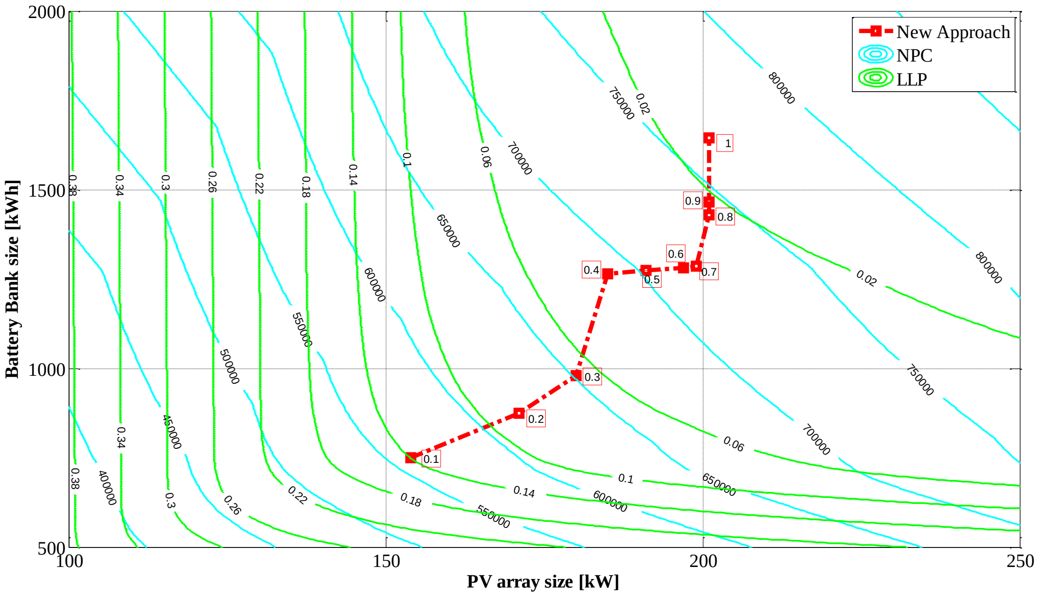


Fig 4.11 New approach of optimization.

Note that, even if it is not the aim of this work, an optimization result in terms of LCOE permits also to compare the PV Micro-Grid as an “Off-Main-Grid” technology with others power technologies (i.e. the connection to the grid or other “Off-Main-grid” renewable based systems). Indeed, as stressed in previous sections, the policy makers or responsible institutions could be interested for example in comparison between the installation of a Micro-Hydro power plant or a PV Micro-Grid on the base of a common decision-making parameter. The same cannot be done with the NPC.

Anyhow, the most important point of the new optimization method is the changing in the sizing approach. Indeed, it recognizes how much more immediate for the designer is to give a valorization of the load not satisfied rather than having to set the percentage of the same load that will not be satisfied. Such this value can be calculated with accuracy based, for example, on the cost for lighting registered by the family cited before, which derives principally from the cost of fuel necessary to switch on a kerosene lamp or the Genset.

In Fig 4.11, in parallel with what exposed in Fig 4.8, the new sizing approach is highlighted. The sizing results are given for valorization of the load unsatisfied that goes from 0.1 €/kWh to 1 €/kWh through a constant step of 0.1 €/kWh.

The results show a particular trend which is a consequence of a trade-off between actual costs and potential costs. Indeed, to higher valorizations of unmet load correspond system increasingly large in terms of installed power and capacity, because a kWh not provided corresponds to high costs for the costumer. Thus, the trade-off leads to prefer spending more in the installation of a larger PV Micro-grid. On the contrary, to lower valorizations of unmet load corresponds smaller systems for the same reason because the trade-off recognizes that the potential costs are not intolerable for the costumer.

Furthermore, the sizing curve in the figure shows that when it is reached a certain valorization of the unsatisfied load, the optimization returns the same size of the PV array continuing, on the contrary, to increase the size of batteries. Such a response can be explained by the fact that to high economic values of the load not satisfied corresponds the need of systems that are able to cover more and more load to avoid the high compensation costs. However, it is also clear that the most critical load to be covered is the one required during the night. Hence, to achieve high levels of coverage of the load, there is no need to further increase the size of the PV but rather the size of the batteries.

Finally, note also that in the new approach the LLP value is not the starting parameter to be fixed as in the classic approach, but a resulting parameter from the optimization phase. Once again, it is emphasized that this is more appropriate for underdeveloped contexts where the definition of the LLP would be senseless.

Next to the results in Fig 4.11 representing the mathematical optimum point corresponding to different valorization of the load not satisfied, it is certainly of fundamental importance to provide an indication of the sensitivity of this optimal point according to an arbitrary variation of the value of the objective function. In this direction, Fig 4.12 shows all the systems that have a value of the objective function that does not deviate by more than 1% from the minimum value, indicated by the red square. Moreover, this figure could be a useful sizing map for the designers for two important reasons:

- It allows the designer to reconnect with the reality of the components available on the local market. In fact, it gives information about the range of systems that can meet the load with a small variation of the objective function. If, for example, the optimization indicates that the best system, for an LL_{value} of 0.3 €/kWh, is the one made of a PV array of 180 kW and a battery bank of 980 kWh, and such system is not feasible with the components available on the market, this map tells to the designers that in the range that goes from 170 kW to 180 kW for the PV array and from 800 kWh to 1300 kWh for the battery bank, the objective function change for less than the 1% of the best value (showed in the red square), the resulting LLP varies from 5% to 10% and the NPC ranges from 600 k€ to 700 k€.
- It clearly shows the regions corresponding to different economic LL_{value} and it is noted that these regions intersect each other. This means that if the designer is not sure of his own estimation he can concentrate on those intersections to size the system.

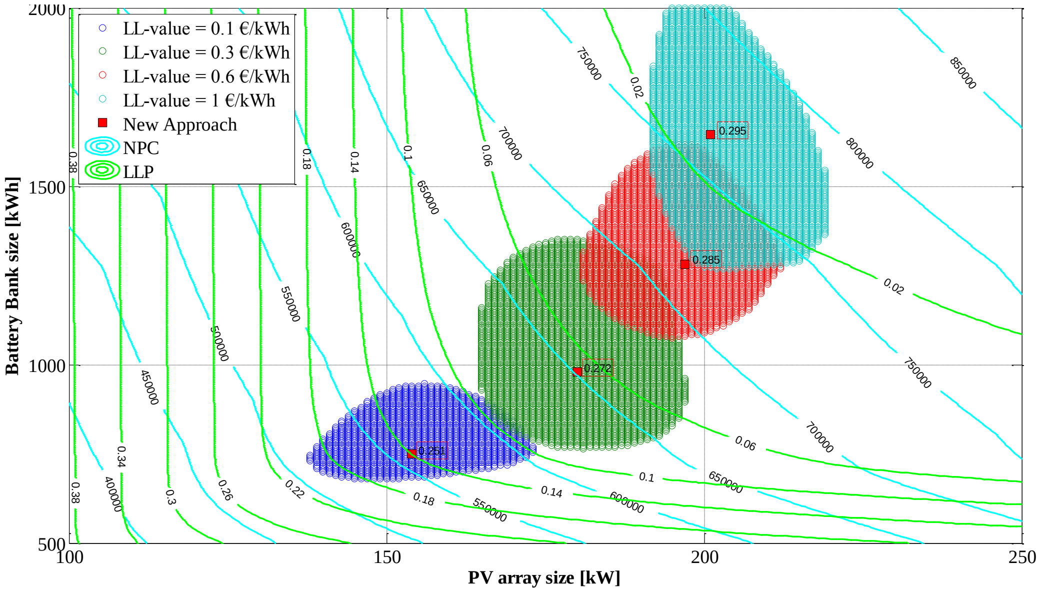


Fig 4.12 New approach of optimization, sensitivity of results.

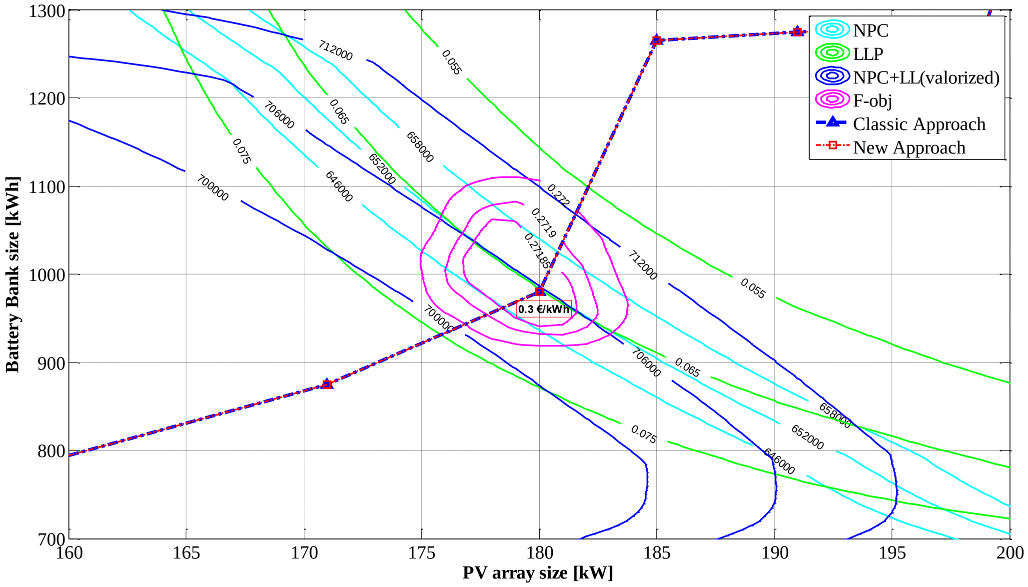


Fig 4.13 Comparison between classic and new approach, the minimum point searching.

Comparison between the different approaches

A further step has been to thoroughly understand how the classic and new approaches influence the search for the optimal system.

In Fig 4.13 the comparison between the two approaches is exposed. The assumption has been to force the classic approach works with the LLP coming from the results of the new approach. It appears that the two approaches coincide each other as emblematically represented by the overlapping of the two blue and red dashed lines.

To better understand, the attention has been focalized on one best point (showed with a red square marker) and precisely the one that corresponds to an LL_{value} of 0.3 €/kWh. As evident, the corresponding system is the optimum solution also in the classic approach (showed as a blue triangular marker). This means that if the system's LLP of about 6.5%, which results from the minimization of objective function (represented with the circle magenta lines), is used as the imposed LLP in the classic method, the resulting system will be the same, localized where such LLP (green line) is tangent with the minimum NPC of about 652 k€ (cyan line).

This result is obvious, because, with reference to the Equation (4.17) and noting that, if the analysis is forced to a constant LLP, all of the terms that make up the expression of the objective function, with the exception of the NPC, are constants, and then the new approach will find the same optimum solution of the classic approach. The only difference is that the optimal point will be found where the curve that corresponds to the fixed LLP is tangent to the curve of the modified NPC equal to 706 k€ (represented with the blue line).

However, note that this is a forcing that has the objective of establishing a link between the two approaches, which is not actually in the availability of the designer. Indeed, a designer, who uses a tool based on the classic approach, finds the problems of above and cannot make the same tool operates with the new approach, because he does not actually know at what LLP of the best system corresponds a particular LL_{value}.

Anyhow, the same analysis permits to underline the most important difference in results between the two approaches represented in Fig 4.14 in which the life cycle costs versus the LLP indicator for the two approaches are presented. Note that, with Life Cycle costs are intended the energetic costs for the users of the PV Micro-Grid.

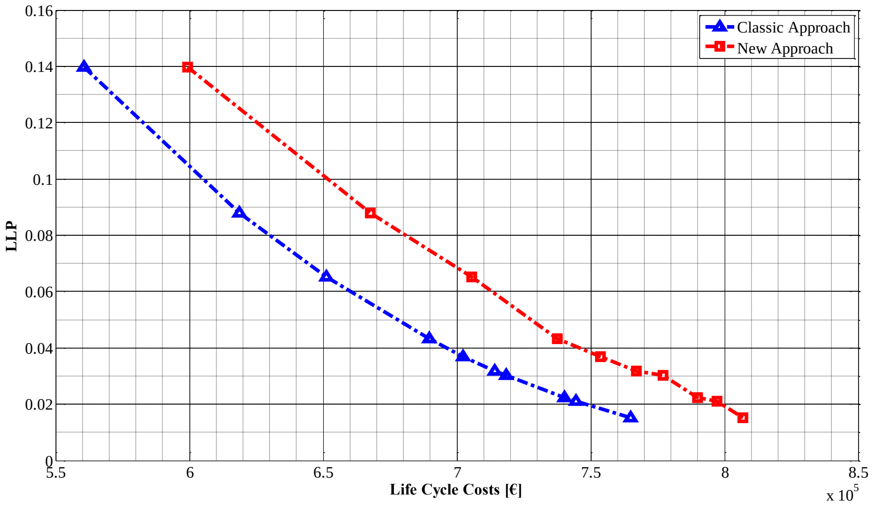


Fig 4.14 Comparison between classic and new approach, the Life Cycle Costs [€].

In the classic approach this means the NPC as calculated in Equation (4.12) while in the new approach it means the modified NPC as computed in Equation (4.14). It is possible to divide the analysis in the case of fixed LLP or in the case of fixed Life Cycle Costs:

- Fixed LLP: in this case the correspondent best system, accordingly with Fig 4.13, is the same for both the approaches. However, if the designer with the classic sizing system, decides that the PV Micro-grid is to be sized on the 10% of the load not satisfied this corresponds to a total NPC over the life cycle of about 600 k€. In any case, this would not be true if the same designer uses the new approach of sizing. In this case the designer would have estimated a LL_{value} between 0.1 €/kWh and 0.2 €/kWh, then he would calculated that the best system for this estimation will returns an LLP of 10% and consequently a total NPC over the life cycle of about 650 k€ derive from the figure, which is well above the previous one. In other words, in the classic approach, the designer starts from the axis of the diagram to detect the optimum point on the blue line, while, in the new approach, the designer starts detecting a point on the red line and then he reads the results from the axes.
- Fixed Life Cycle Costs: in this case the correspondent best system is not the same for the two approaches. Indeed, if it is assumed to know the total amount of actualized money to be spent over the life cycle, the new approach provide as result a system which have an higher LLP and obviously composed by smaller components, because in the same amount of money need to be comprised all the energetic costs.

4.2.4 Model evolution

Having defined the optimization criterion, the final step has been to outline the evolution of such optimum result to changes in the physical model simulated. As previously anticipated, the physical model has been developed starting from an ideal description and introducing more detailed components model gradually according to the most established scientific-literature based models.

To be able to compare different results coming from different simulations some input data have been set as common:

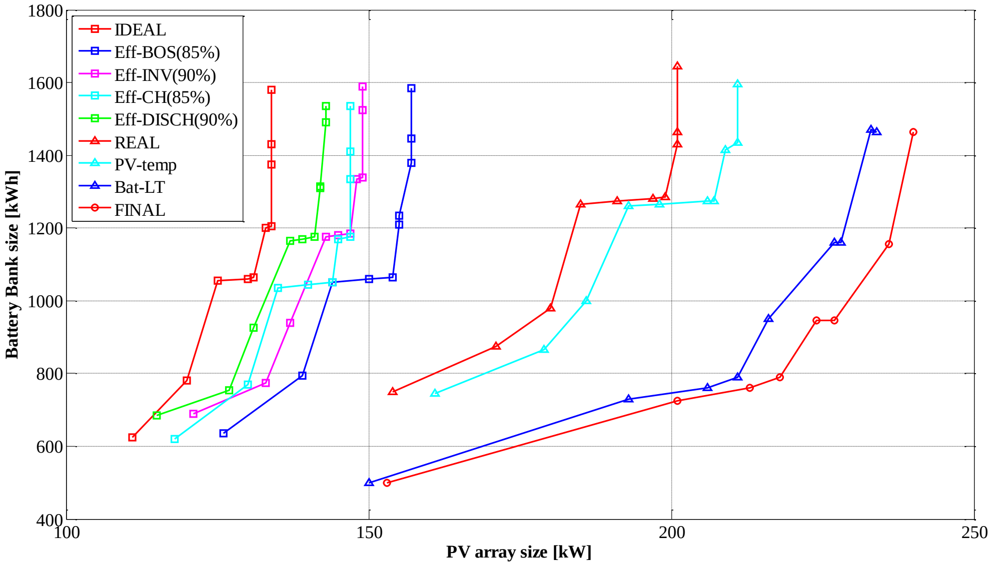


Fig 4.15 Evolution of best system sizing curve.

- The hourly time step.
- The simulation range, which goes from 100 kW to 250 kW for PV array power with a simulation-step of 1 kW and from 500 kWh to 2000 kWh with a simulation-step of 5 kWh for the battery bank.
- The solar resource, taken from *HOMER* for the mentioned location of Soroti.
- The valorizations of the unmet load, that goes from 0.1 €/kWh to 1 €/kWh through a constant step of 0.1 €/kWh.
- Cost assumptions, based on the rural context of Uganda.
- The inverter size, which has been sized on the maximum power required by the load as explained in Section 4.2.1.

In this framework, it is possible to resume the logic of the simulations, the results of which is exposed in Fig 4.15, in five steps:

1. The ideal model (red line with square marker): that represents the starting point. In this first step all the efficiencies have been set to 100% and the two main components have been modelled as ideal, with no effect of temperature on the PV array and with the ideal battery lifetime model implemented. As showed, the ideal sizing curve, according with different unmet load valorizations, goes from 110 kW to 130 kW for PV array power and from 600 kWh to 1600 kWh for the battery bank. Also in this case, the greater variability in the size of the battery bank when compared with that of the PV array can be explained as made with Fig 4.11.
2. Introduction of efficiencies (coloured lines with square markers): all the efficiencies exposed in Section 4.2.1 have been introduced as second step one at a time. Some of them have effects on the PV array, some on the battery bank and others on both the components. For example, while the charging efficiency has effect on the size of the PV array since a bigger PV array is required to charge the same battery bank, the discharging efficiency, on the contrary, has effect on the size of the battery bank because a bigger battery bank is needed to meet the same load. Note that all the resulting effects change with different unmet load valorization. This aspect can be explained with the particular expression of the objective function that, looking for

the best system principally on an economical criterion, leads the best system to move according to an economic logic.

3. The “real” model (red line with triangular marker): summing all the effects given by every particular efficiency introduced in the modelization, has been possible to obtain the “real” model.
4. Modelization of components’ behaviour (coloured lines with triangular markers): the next step has been to introduce a better description of the two main components of the system. Regarding the PV array the influence of cell’s temperature, as explained in Equation (4.3), has been taken into consideration. Since this aspect affects the power output of the modules, the consequences on the sizing curve are all attributed to the PV array, because a bigger field of photovoltaic modules is needed to produce the same energy output. Concerning the battery bank, the “rainflow” cycles counting method, as explained in Section 2.3.2, have been implemented. In this case, the effects are on both the components. Indeed, since this model leads to the estimation of a greater number of battery bank’s replacement during the useful life of the system, this aspect, according with the assumptions about the costs of the components, leads to prefer a system with a higher power of the PV array and a lower battery bank capacity installed.
5. The Final model (red line with circle marker): that takes into account all the above steps. As showed in the figure the final sizing curve, according with different unmet load valorizations, goes from 150 kW to 240 kW for PV array power and from 500 kWh to 1500 kWh for the battery bank.

4.3 Case study: PV Micro-Grid in the rural context of Uganda

The case study is located in the rural area surrounding the city of Soroti, in the central-east district of Uganda, a small but expanding town in strong economic growth where the electric grid reaches only few business activities and houses in the city centre. The climate potential of the region is really interesting, the stable and sunny weather with high monthly mean values of insolation, make Soroti the ideal place for PV Micro-Grid installation. As it has been verify on the field by the author, the majority of households and activities use diesel generators (Genset) to bring electricity in their houses or work place. However, there are residential areas where extremely poor families live without electricity and they make use of other systems to satisfy basic needs, for example kerosene lamps to have lighting during night hours. In this context, addressing the electrical needs of a typical rural area in Uganda with a PV Micro-Grid, as in most developing countries in the 21st century, means to bring electrification to the poorest part of the users and a more clean, efficient and reliable energy for the remaining part.

4.3.1 Results with numerical model in MATLAB®

The objective of this paragraph is to present the assumptions and the consequent sizing results of a PV Micro-Grid based on the numerical model developed in MATLAB® following the new methodology explained in previous sections. The intentions are also to show how the use of this new approach can allow taking into account the real context of loads, which can be composed by users of different type, the needs of which should influence the sizing results.

Table 4.2 Case study, sample of class type collected data.

CLASS TYPE	**N°$_{US}$**	**APPLIANCE NAME**	**P[W]**	**N°$_{App}$**	**h_{funct}**	**N°$_{Win}$**	**W_1**		**W_2**		**W_3**		**h_w**
Family_1	**50**	Lights (normal)	3	4	6	2	0	2	17	24	-	-	9
		Phone Charger	5	2	3	3	0	9	13	15	17	24	18
		Security Light	5	1	12	2	0	7	17	24	-	-	14

Load estimation

The first step has been to estimate the load of the users to which the PV Micro-Grid must provide electricity. Based on the real context, a rural village made of 100 households, divided in 6 groups according with different energy needs, and other typical activities (enterprises, kiosks, market place, school, etc.) for a total of about 1000 people involved, has been delineated. Firstly, the addressed users have been standardized in different class types and then, the load data have been collected.

In Table 4.3 the data collected for the Family_1 class type are presented. As showed, this class type forms a group of 50 users and presents the same energy needs, graphically exposed in the list of appliances. All the others data have been already explained with reference to Table 4.1 and they serve to calculate the energy consumption of the selected class type during a day ($E_{CLASS,DAY}$) and its distribution over the day hours. In Table 4.3 the energy consumption for each class type, the data of which have been fully exposed in Table B.0.5 in Appendix B, are exposed. For each class type also the Energy consumption for the single user on daily ($E_{USER,DAY}$) and yearly ($E_{USER,YEAR}$) basis have been calculated. With reference only to family types and assuming 8 persons per households [19], also the electrical energy consumption per capita ($E_{CAP,YEAR}$) has been derived.

The resulting day load is of about 663 kWh. The energy requirements are distributed as shown in Fig 4.16 with a maximum power need of about 50 kW. Obviously, since the load curve has been reconstructed as explained in Section 4.2.1, the same limitations are remarked also in this case.

Table 4.3 Case study, class types results

CLASS TYPE	**$E_{CLASS,DAY}$ [kWh/day]**	**N°$_{US}$**	**$E_{USER,DAY}$ [kWh/day]**	**$E_{USER,YEAR}$ [kWh/year]**	**$E_{CAP,YEAR}$ [kWh/year*cap]**
Family_1	8.1	50	0.16	59.1	7.4
Family_2	10.2	15	0.68	248.9	31.1
Family_3	31.0	15	2.06	753.4	94.2
Family_4	31.4	10	3.14	1146.5	143.3
Family_5	30.7	5	6.14	2240.4	280.0
Family_6	41.4	5	8.28	3023.3	377.9
Enterprise_1	98.7	15	6.58	2401.7	-
Enterprise_2	130.8	5	26.17	9550.2	-
Mobile Money	2.0	5	0.39	143.4	-
Kiosk	67.6	10	6.76	2468.5	-
Barber	4.6	2	2.32	846.8	-
Tailor	2.6	3	0.87	317.6	-
Market Place	25.5	1	25.53	9316.6	-
Club	91.1	3	30.35	11077.8	-
Street Lights	69.0	1	69.00	25185.0	-
Primary School	1.8	1	1.79	651.5	-
Pharmacy	16.9	1	16.85	6150.3	-
TOTAL LOAD	**663.4**				

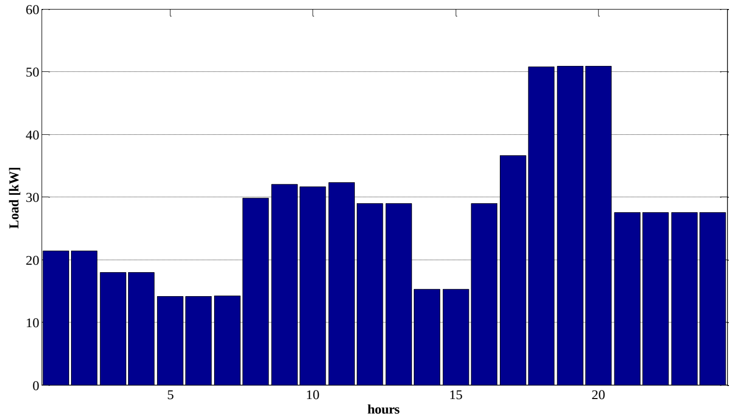


Fig 4.16 Case study, resulting load curve.

Note that data, which have been used to obtain the load curve, acquire consistency and appropriateness to the context when is considered that:

1. The electrical need of households is of about 153 kWh. This represents the 23% of the total load, percentage that is in line with the country energy balance of 2011 exposed in Fig 1.4 in which the TFC of main grid electricity in the residential sector is exactly the 23%.
2. The average electrical power consumption per capita can be calculated of about 70 kWh/year which, also in this case, is in line with the 2011 electricity consumption per capita of 64.5 kWh showed in Fig 1.8.

Solar resource

Next step has been to obtain the solar resource data. Mean daily solar irradiation and ambient temperature values (Table 4.4) for every month of the year for the location of Soroti in Uganda (1.72N / 33.6E) have been taken from the website of the NASA atmospheric science data center [66]. Then, as been explained in Section 4.2.1, this data have been put in *HOMER* that, relying on the HDKR model, elaborates the above data and calculates as output the global solar radiation incident on the surface of the PV array and the cell temperature for each hour over the year to be used in the MATLAB® model to obtain the PV array energy output. The results of this process have been already showed in Fig 4.2 for the first five days of the year.

Table 4.4 Case study, mean daily Irradiation and ambient temperature values for Soroti.

Month	**Mean daily Irradiation [kWh/m^2 day]**	**Ambient Temperature [°C]**
January	6.22	21.91
February	6.56	22.50
March	6.36	21.94
April	5.99	21.12
May	5.72	20.72
June	5.39	20.70
July	5.29	20.80
August	5.67	21.11
September	6.22	20.85
October	6.01	20.52
November	5.83	20.59
December	6.07	21.17

Table 4.5 Case study, physical model assumptions.

MODEL ASSUMPTIONS			
PV ARRAY			
Balance of system efficiency	η_{BOS}	85	%
Cell Temperature effect	T_{Cell}	yes	
Temperature coefficient of power	ρ	-0.4	%
STC temperature	T_{Rif}	25	°C
BATTERY BANK			
Minimum State of Charge	SOC_{min}	40	%
Power-energy ratio	$(P/E)_R$	50	%
Charge efficiency	η_{CH}	85	%
Discharge efficiency	η_{DISCH}	90	%
“rainflow” cycles counting		yes	
INVERTER			
Inverter efficiency	η_{Inv}	90	%

Physical model

Having the two main data inputs (load curve and solar resource profiles), the further step has been to choose the settings to run the simulations in the MATLAB$^{®}$ model. With reference to Section 4.2.4, the physical model has been set to the final evolution, which presents the feature in Table 4.5, which can be resumed in:

- The Components’ efficiencies: all the efficiencies exposed in Section 4.2.1 have been introduced.
- The influence of cell’s temperature on PV array.
- The influence of the “rainflow” cycles counting method on the battery lifetime prediction.

Cost assumption

The next step has been grouping those data necessary (Table 4.6) to calculate the NPC of the systems simulated by the MATLAB$^{®}$ model. Regarding the two main components (i.e. PV array and battery bank), cost information referring to the Ugandan context has been collected by the author as previously exposed in Fig 1.15 and Fig 1.16. Other important information has been obtained courtesy of MCM Energy Lab, a spin-off of the Politecnico di Milano.

Table 4.6 Case study, Cost assumptions.

Item	**Type/Info**	**Source**	**Rate**	
PV modules	Monocrystalline	Local supplier in Uganda	1000.00	€/kW
Battery	Lead-Acid (sealed)	Local supplier in Uganda	140.00	€/kWh
Inverter	Calculated on the peak of the Load	MCM Energy Lab	500.00	€/kW
Others costs	Percentage on the cost of investment	[78]	20	%
O&M		MCM Energy Lab	50.00	€/kW*year
Plant Life Cycle			20	Years
Real interest			6	%

Value calculation of the load not satisfied

The most important step is the valorization of the unsatisfied load since it is indispensable to compute the objective function and to decide the sizes of main components of the PV Micro-Grid.

As mentioned before, in the rural context under consideration the majority of households and activities use Genset. However, there are residential areas where poor families live without electricity and they find other solutions to satisfy basic needs. In this direction, the calculation of the LL_{value} needs to take into account this dichotomy between users who had electricity generated by other system and users who did not have electricity before the installation of the PV Micro-Grid. To calculate final valorization of the load unsatisfied some assumptions, listed in Table 4.7, need to be done. The general idea has been to assume that, in both cases, users of each category face the load unsatisfied returning to use the previous system. There is no assurance that this will be the real behaviour of people in the case of a PV Micro-Grid black out, but this is the more conservative assumption to calculate the valorization of the unmet load.

Users with electricity

With reference to Table 4.3 all classes' type, with exclusion of family_1, has been assumed they had made use of genset before. In this group of users, which has been named category_1, the costs to cover the unsatisfied load are linked to the fuel necessary to run the diesel engine.

Based on assumption exposed in Table 4.7, since the kWh not satisfied by the PV Micro-Grid need to be produced by the genset, firstly the calculation of the primary energy required to generate a kWh not supplied (LL_{Ref}) is needed:

$$\frac{E_{p,Diesel}}{LL_{Ref}} = \frac{1kWh}{\eta_{EE,Genset}} = 2.86\ \frac{kWh_{p,Diesel}}{kWh_{ns}} \tag{4.18}$$

Then, the calculation of the volume of fuel to be purchased is the next step:

$$V_{Diesel} = \frac{E_{p,Diesel}}{v_{Diesel}LHV} = 0.28\frac{l}{kWh_{ns}} \tag{4.19}$$

Having collected price of the fuel on the field, it has been possible to calculate the valorization of the unsatisfied load for such category_1 of users:

$$(LL_{value})_1 = V_{Diesel}\frac{p_{Diesel}}{\mathrm{EXC}} = 0.24\ \frac{€}{kWh_{ns}} \tag{4.20}$$

Table 4.7 Case study, assumption for the valorization of the unsatisfied load.

ASSUMPTIONS			
Genset electrical efficiency	$\eta_{EE,Genset}$	35	%
LHV Diesel	LHV	12.33	kWh/kg
Specific volume Diesel	v_{Diesel}	0.825	kg/l
Price diesel	p_{Diesel}	3,000.00	UGX/l
UGX-€ Exchange	EXC	3,500.00	UGX/€
Phone battery capacity	$C_{Bat,Ph}$	1000	mAh
Price charging phone	$p_{CH,Ph}$	300.00	UGX
Household lighting expenditure in kerosene	$C_{Lgt,k}$	30,000.00	UGX/month

Users without electricity

As anticipated, to this group, which has been named category_2, belongs only the family_1 class type. This group is composed by 50 households, which have the basic need of lighting and charging phones (it is recalled that the credit system in Uganda is based on currency movements through services on the mobile platform). Thus, the calculation of two separated valorizations of the unsatisfied load is required.

Regarding lighting system it is assumed that, in case of PV Micro-Grid black out, users decide to continue having inside lights leaving switched off the security light. The use of kerosene lamps is assumed since it is the prevalent lighting technology in developing countries in households with no access to electricity. To compare electrical bulbs and kerosene lamps what has been maintained constant are the number of light hours. Thus, with reference to Table 4.2, since the power consumption of the lighting system (P_{Lgt}) is of 12 W, this means that to a kWh not supplied corresponds a certain number of not supplied lighting hours ($h_{Lgt,ns}$).

$$\frac{h_{Lgt,ns}}{LL_{Ref}} = \frac{1kWh}{P_{Lgt}} = 83.33\ \frac{h_{ns}}{kWh_{ns}} \tag{4.21}$$

Then, from the same table, it is possible to calculate the monthly hours of lighting ($h_{Lgt,m}$) required by family_1 class type as follows:

$$h_{Lgt,m} = h_{funct,Lgt} dd_{month} = 180\ \frac{h}{month} \tag{4.22}$$

With $h_{funct,Lgt}$ and dd_{month} are respectively the daily functioning hours of the lights and the number of day in a month. Then, having assumed a monthly amount of expenditure ($C_{Lgt,m}$) for lighting of an average household with no access to electricity (with reference to Section 1.5), it has been possible to derive the specific cost of a light hour provided by a kerosene lamp ($c_{Lgt,k}$) as follows:

$$c_{L,k} = \frac{C_{L,m}}{h_{Lgt,m}\ EXC} = 0.048\ \frac{€}{h} \tag{4.23}$$

Thus, having calculated the specific cost of a light hour and the number of not supplied lighting hours that corresponds to a kWh not supplied by the PV Micro-Grid, the final step is to calculate the valorization of the lighting load not satisfied:

$$(LL_{value})_{Lgt} = h_{Lgt,ns} c_{Lgt,k} = 3.97\ \frac{€}{kWh_{ns}} \tag{4.24}$$

Concerning phone charging the alternative solution is to charge phone from kiosk or market place that give such service as represented in Fig 1.13. An average battery capacity to be recharged has been chosen and a common charging voltage ($V_{CH,Ph}$) of 5 Volts has been assumed to calculate the energy required to charge the phone as follows:

$$E_{Bat,Phone} = C_{Bat,Ph} V_{CH,Ph} \tag{4.25}$$

Then, to calculate the phone charging load not satisfied, a typical medium price to charge a phone has been assumed as showed in Table 4.7.

$$(LL_{value})_{Ph} = \frac{p_{CH,Ph}}{E_{Bat,Ph}\ EXC} = 17.14\ \frac{€}{kWh_{ns}} \tag{4.26}$$

Table 4.8 Case study, valorization of the unsatisfied load.

VALORIZATION OF THE UNSATISFIED LOAD			
Category_1	$LL_{value\ 1}$	0.24	€/kWh
Category_2: Lighting	$LL_{value\ Lgt}$	3.97	€/kWh
Category_2: Phone charging	$LL_{value\ Ph}$	17.14	€/kWh
Category_2	$LL_{value\ 2}$	7.92	€/kWh
Final	$\mathbf{LL_{value}}$	**0.33**	**€/kWh**

Thus, to calculate the valorization of the unsatisfied load for category_2 the relative weight of the two types of load required by family_1 need to be taken into account. Looking to Table 4.2, it is possible to calculate that the lighting load represents the 70% of the total needs and the phone charging the remaining 30%.

$$(LL_{value})_2 = (LL_{value})_{Lgt} w_{Lgt} + (LL_{value})_{Ph} w_{Ph} = 7.92 \frac{€}{kWh_{ns}} \quad (4.27)$$

Finally, having calculated the valorizations of the unsatisfied load for the two categories (users who had electricity generated by other system (category_1) and users who did not have electricity (category_2) before the installation of the PV Micro-Grid), to calculate the final valorization the relative weight of the two category on the total load need to be taken into account. Looking to Table 4.3 it is possible to calculate that category_1 represents the 98.8% of the total day load and the category_2 the remaining 1.2%.

$$LL_{value} = (LL_{value})_1 w_1 + (LL_{value})_2 w_2 = 0.33 \frac{€}{kWh_{ns}} \quad (4.28)$$

All the valorizations of the unsatisfied load calculated above have been resumed and showed in Table 4.8.

Sizing results

In the next lines, simulation results are exposed. All the inputs necessary to make the MATLAB® model works have been explained in previous sections and can be resumed in short:

- The time step: hourly time step has been chosen.
- The simulation range: it goes from 150 kW to 300 kW for PV array power with a simulation-step of 1 kW and from 500 kWh to 1500 kWh with a simulation-step of 5 kWh for the battery bank.
- The solar resource: mean daily solar irradiation and ambient temperature values (Table 4.4) for every month of the year for the location of Soroti in Uganda have been taken from the website of the NASA atmospheric science data center and they have been put in *HOMER* to obtain the global solar radiation incident on the surface of the PV array and the cell temperature for each hour over the year.
- The valorizations of the unmet load: it has been calculate above in the value of 0.33 €/kWh as showed in Table 4.8.
- The cost assumptions, they have been imposed based on the rural context of Uganda as showed in Table 4.6.
- The inverter size, which has been sized on the maximum power required by the load as explained in Section 4.2.1.

Table 4.9 Case study, sizing results.

SIZING RESULTS		
PV array size	214	kW
Battery bank size	790	kWh
Inverter size	57	kW
F-obj / LCOE modified	0.382	€/kWh
NPC	947	k€
NPC modified	1000	k€
LLP	5.8	%

As showed In Table 4.9, the minimum of the objective function is of about 0.38 €/kWh for a system with a a PV array of 214 kW and a battery bank of 790 kWh.This system will cost 1 million of Euro over the life cycle and will guarantee an LLP of about the 6%.

It is stressed how this MATLAB® model is far to be a sizing tool that takes into account the existing sizes of components which can be really purchased on the market to install the PV Micro-Grid. In this framework, it is marked the difference with what done in Chap. 3 with the *VE Sizing&Princing* tool which has been defined as an appropriate sizing tools since it actually takes into account a database of real components. On the contrary, the appropriateness of the MATLAB® model has been limited to the new approach of sizing that passes through the valorization of the unsatisfied load. With these clarifications, sizing results of Table 4.9 represent a preliminary sizing phase. To complete the installations of the PV Micro-Grid other assumptions need to be done by the designer in order to be able to face the reality of the context under consideration.

However, as previously explained in Section 4.2.3, Fig 4.17 has the intent to help the designer in this direction. Indeed, showing all the systems that have a value of the objective function that does not deviate by more than 1% from the minimum value, it gives information about the range of systems that can meet the load with a small variation of the objective function. If, for example, the optimum system indicated in the above table is not feasible with the components available on the market, this map tells

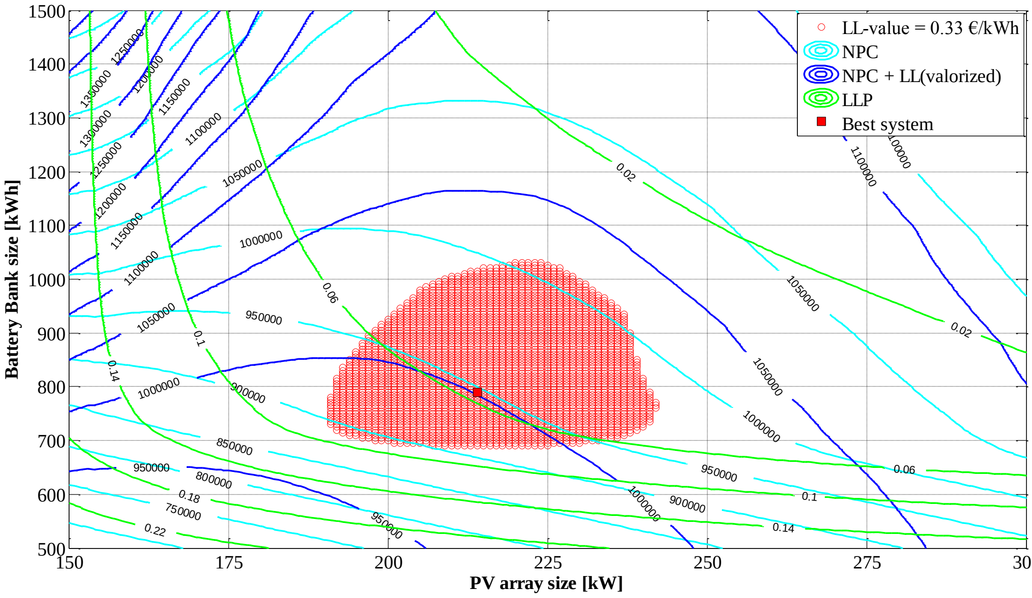


Fig 4.17 Case study, sizing result. Variability due to objective function.

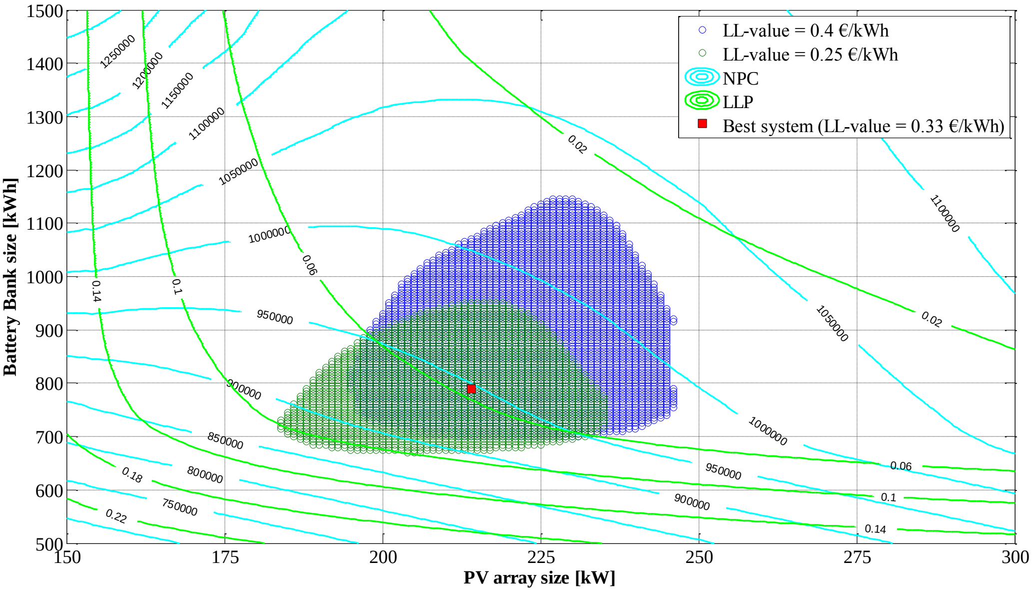


Fig 4.18 Case study, sizing result. Variability due to valorization of unsatisfied load.

to the designers that in the range that goes from 190 kW to 240 kW for the PV array and from 700 kWh to 1000 kWh for the battery bank, the objective function change for less than the 1% of the best value (showed in the red square), the resulting LLP varies from 3% to 10% and the modified NPC ranges from 970 k€ to 1040 k€.

Fig 4.18 shows sizing optimum regions for different valorizations of the unsatisfied load. As represented, the best system of above, which results from a designer's estimation of the valorization of the unsatisfied load, is included also in optimum region for LL_{value} that vary by approximately 20% from such estimated value. This means that designer's estimation errors can be adsorbed when the reality of component's needs to be faced by the designer.

4.3.2 Results with intuitive method and *HOMER*

The purpose of the section is to verify that the results, obtained with the MATLAB® model, are consistent with ones that would be obtained by the application of the two most commonly sizing methodologies used in literature: (i) the basic intuitive method and (ii) the classic approach of the numerical method which is used in *HOMER*.

Regarding the intuitive method, the sizing approach used has been explained in Section 2.3.1. Results are quite similar to those that could be obtained in the preliminary sizing phase of the *VE Sizing&Pricing* tool.

To better understand and compare results, two sizing approach of the battery bank were probed:

Table 4.10 Case study, sizing results with intuitive method

	Night Coverage		**1 Cloudy Day**	
PV array size	173	kW	173	kW
Battery bank size	385	kWh	1106	kWh
Inverter size	57	kW	57	kW
NPC	546	k€	900	k€

- Night Coverage: as expressed by Equation (2.3), this approach is to dispose of a battery bank capable to give the energy required by the load during the night.
- 1 Cloudy day: in this case, as expressed by Equation (2.4), the approach is to size the battery system in order to satisfy one no-sun day.

As presented in Table 4.10, final results are quite different with ones obtained with the MATLAB® model.

The size of the PV array is much lower. This fact can be explained both by the non-presence of the effect of cell temperature on the productivity of the modules, both by the inability of the intuitive method to simulate the system and identify the critical operation. Indeed, while the MATLAB® model expresses these problems with the calculation of LL, the intuitive method cannot figure it leaving the user with no parameters that describe the reliability of the system.

Regarding the size of the battery bank it depends on which approaches is chosen. If it is the night coverage, the size is lower because it is simply sized on the night load taking into account the minimum allowable SOC and battery efficiency. If it is the cloudy day coverage, the size is greater than the one resulting from the MATLAB® model because the latter, being able to simulate the plant behaviour hour by hour, it can size exactly the battery bank without the assumption of having to always be ready to face a no-sun day.

Also economic results in the form of NPC are different and this is principally due to the replacement's cost. Indeed, battery replacement in intuitive method is not linked with the real functioning of the storage. A number of maximum cycles have been assumed (in coherence with the one exposed in Table 4.5) and the correspondence between day and cycle has been made.

Concerning *HOMER*, it has been set with all the same inputs and assumptions valid for the MATLAB® model. The only marked difference is on the merit of the battery bank. In fact, *HOMER* is extremely real-context based on this aspect, the voltage of the system and a particular battery need to be chosen according with user preference. Thus, the DC bus voltage has been set to 110 Volts and two different type of battery from different makers present in *HOMER* database has been chosen, namely:

- Hoppecke 24 OPzS 3000: a big battery of 3000 Ah at 2 Volts which have the benefit to reduce the number of pieces necessary to reach the desired total energy to be stored. The negative point is the difficulties in finding batteries of this size in the real markets in developing countries, so to overcome this problem it may be necessary the import such products.
- Vision 6FM 200D: a small battery of 200 Ah at 12 Volts which has the quality of being a common type of battery certainly available also in developing countries' markets.

Table 4.11 Case study, sizing results with *HOMER*

	Hoppecke **2 V 3000 Ah**		***Vision*** **12 V 200 Ah**	
PV array size	190	kW	210	kW
Battery bank size	990	kWh	1037	kWh
Inverter size	60	kW	60	kW
LCOE	0.235	€/kWh	0.439	€/kWh
NPC	616	k€	1146	k€

As presented in Table 4.11, final results are comparable with ones obtained with the MATLAB® model. It is stressed that to obtain such results a maximum allowable LLP of 6% (according with the LLP in Table 4.9) has been imposed.

The size of the PV array is quite different. This fact can be explained in the differences between the decision-making approaches of the two systems. In fact, while the MATLAB® model follows the new approach exposed in previous pages, *HOMER* follows the classic approach as exposed in Section 4.2.3.

Regarding the size of the battery bank, the differences are significant in both cases. Explanations need to be found in the differences between the battery's descriptions implemented in the MATLAB® model and in *HOMER*. Certainly *HOMER* is more accurate in the modelization of the real battery's functioning, however, it has been noticed a lack in the description of battery's life time, which, on the contrary, has been taken under consideration in the MATLAB® model as the last step of modelization.

All the above differences reflect in economic result in the form of NPC and LCOE (which in *HOMER* is calculated as in Equation (4.16). In Table 4.11 it is showed a big difference between the two cases under considerations. This is due to battery replacement cost that in the case of Hoppecke batteries are lower than in case of Vision battery. Indeed, Hoppecke 24 OPzS 3000 are extremely long-life batteries that need to be replaced only every ten years when properly installed in a ventilated room with the correct ambient temperature and if properly controlled and maintained. However, it has to be noticed that in real context like the one into consideration is very difficult to find this condition available. On the contrary, Vision batteries are more local-appropriated when thinking about developing countries, the replacement of the battery bank is more frequent and this is showed also by the similarity of the correspondent NPC with the NPC obtained in the MATLAB® model.

Conclusions

In this work, “Off-Main-Grid” Photovoltaic Systems have been investigated with particular attention to develop appropriate sizing methods for Stand-Alone Photovoltaic systems (SAPV) and PV Micro-Grid in developing countries.

The problem of energy with particular reference to rural electrification is the general context of the thesis. The internship period at Village Energy Uganda Ltd. has enabled the author to deeply understand these issues on the field thus providing the specific context of Uganda, deeply exposed In Chap.1, in which locate the case studies presented in the thesis, but, above all, to collect the information and data in order to validate the appropriateness of the proposed methodologies.

The study of literature has provided a solid foundation for the development of the following work. The “Off-Main-Grid” Photovoltaic systems have been deeply investigated in Chap. 2 through a review of the sizing methodologies developed in the scientific literature and the most common software available. Two sizing methods, namely the intuitive and numerical method, and the commercial software *HOMER* have been described in details

The *VE Sizing&Pricing* tool created by the author as an appropriate Microsoft Excel decisions-support instrument for the case of Village Energy, which helps the user to size an SAPV system and make quotation for the client has been presented in each of its component parts in Chap. 3.

Based on the experience gained by the author after two months spent in the operational reality of Village Energy Ltd, the *VE Sizing&Pricing* has been concluded to be more appropriate for their necessity if compared, on the same case study, with *HOMER* in which numerous aspects pose serious limits to its adaptability and flexibility. In particular it has been underlined that the *VE Sizing&Pricing* presents all the features, which have been required by the Village Energy management. (i) It is *simple but accurate*, it requires some inputs from costumer and automatically guides the user towards the compilation of the quotation to be printed for the client. (ii) It is *fast*, being designed to operate automatically by taking advantage from information already pre-set, it permits to the user to generate a quote in few minutes. (iii) It is *flexible*, the numerous cells that can be changed in each Microsoft Excel sheet make it able to adapt to any particular request of the client. (iv) It is *market-based*, it presents a detailed database that stores all the components used by the company in its installation. Thus, the final results are adapted to the particular context, in terms of components that actually exist on the market. (v) It is *editable in the future*, the database, the sizing approach and the economic assumptions can be changed whenever it needs.

As a future development, the collection of additional information from the customer about the current energy costs to automatically provide a comparative analysis with information about return on investment, should be taken into consideration in order to provide more details to the customer and let him decide not only based on the cost of investment.

The numerical model implemented in MATLAB®, with emphasis to the new features introduced in order to develop an appropriate numerical PV Micro-Grid sizing method for real-context based application in developing countries, has been presented in Chap. 4.

The proposed MATLAB® model has been concluded to be more appropriate to size a PV Micro-grid due to the criterion (i.e. the objective function) that uses to choose the best combination of components that addresses the load. Indeed, it has been recognised how the literature approach of sizing (implemented also in *HOMER*), which consists in matching the load demand under a specific LLP, fixed by the designer, at the minimum

NPC over the life cycle of the system, presents three main limitations when referring to real context in un-electrified areas of developing countries:

- *The impossibility to define the LLP*, it is actually not realistic to think that the designer or the customer reached by the PV Micro-grid know which is the maximum load that can be lost, thus it has been recognized the need for a new approach that moves the selection on a more appropriate plane.
- *The Net Present Cost does not take into account all the cost* over the life cycle of the PV Micro-Grid. Since the PV Micro-Grid leaves uncovered some loads during the year, meaning that people may return to previous system spending more money not included in the calculation of the NPC, the valorization also of this aspect appeared to be appropriate.
- *The optimization phase is in two steps*: since the designer have to find firstly all the systems that address the load with the fixed LLP value and order the corresponding NPC of the same systems in a second step to find the one with the minimum value, it seemed appropriate to speed up the process of optimum determination.

In this perspective, the elaboration of a new approach, in contrast to the classical one, has had the aim to give answers to these limitations, with:

- *The setting of an economic value for the load not satisfied by the PV Micro-Grid*: it recognizes how much more immediate for the designer is to give a valorization of the load not satisfied rather than having to set the percentage of the same load that will not be satisfied.
- *The calculation of a modified NPC:* the loss of load cumulated during the simulated year of operation is a new negative cash flow to be computed in order to obtain a NPC pertinent to the PV Micro-Grid installed as a full energetic system.
- *The use of an appropriate objective function:* having recognised that such modified NPC is not enough to find the best system because this would be to choose the minimum based only on economic criteria without taking into account the satisfaction of the load, the LCOE, modified with the introduction of such NPC, has been chosen as objective function since at the numerator it presents the economic factor and at the denominator the customer’s satisfaction in terms of how much of the load is actually satisfied. Last but not least, this objective function shows directly, in one step, a minimum value representative of the best system.

Moreover, having detected how this MATLAB® model is far to be a sizing tool that takes into account the existing sizes of components which can be really purchased on the market, the sizing results obtained examining a proposed case study are to be intended as a preliminary sizing phase which give useful information at the planning level. As final step, in order to give response also to this limit, a sizing map, which gives information regarding the sensitivity of the optimal point according to an arbitrary variation of the value of the objective function, has been proposed with the aim to allow the designer reconnecting with the reality.

As future developments, additional study on the estimation of the load curve is required with the aim of having a load curve temporally more detailed. It is therefore also advisable to coherently reduce the simulation time-step, developing descriptive models of components, which are able to exploit the new temporal detail with special attention to the stability and reliability of the system. In this direction, the development of more accurate battery’s model especially regarding the determination of SOC in relation to the working conditions, it is of primary importance. Finally, recognizing that the evaluation of the valorization of the unsatisfied load has been conducted without a deep analysis of possible available approaches, it is also required to study the specific literature and to consider the possibility to develop a more detailed methodology that can be adapted for the particular application of the present work.

Appendix A

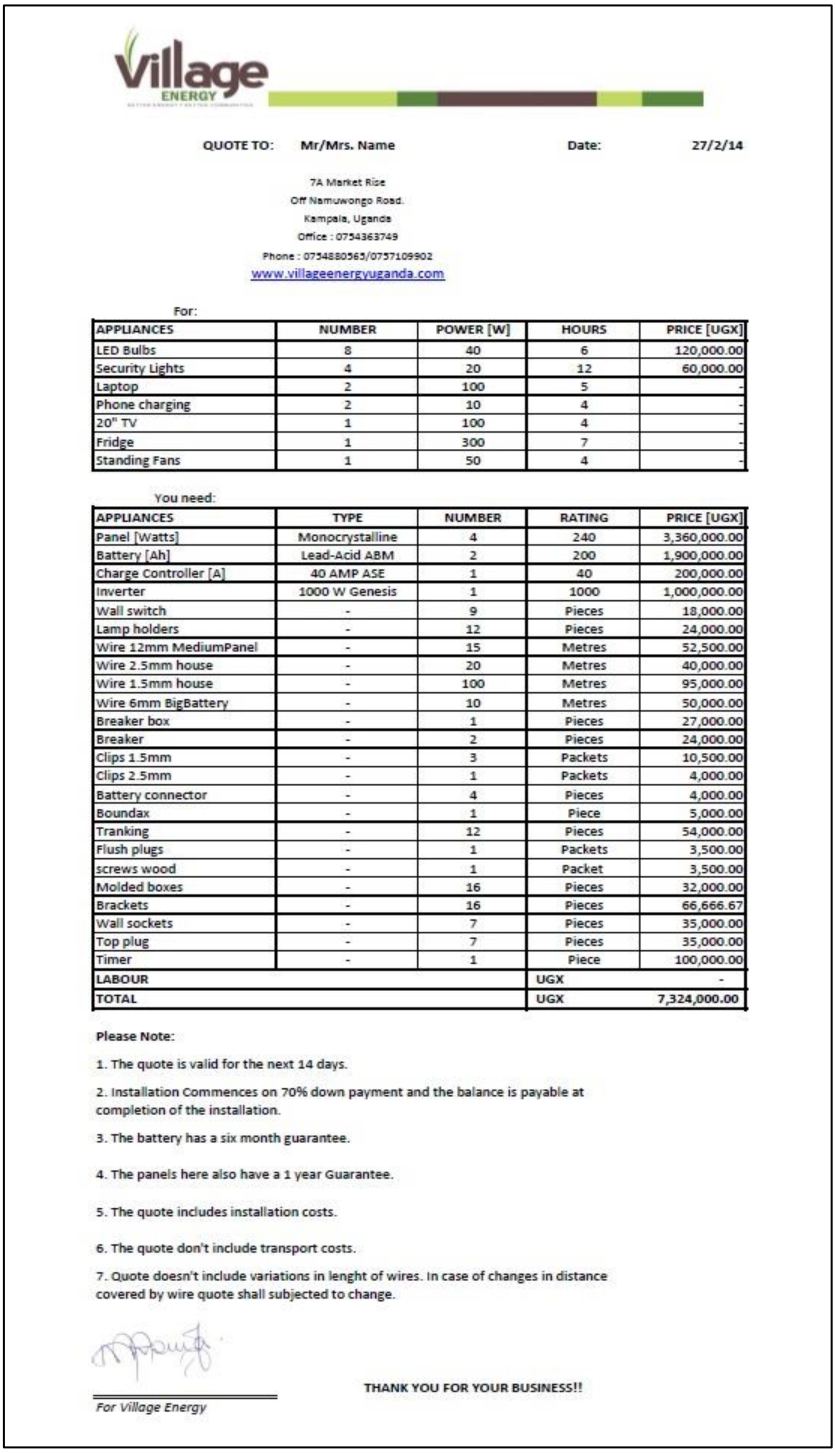
Ugandan data

Table A.0.1 TPES and TFC balance for Uganda (2011). Author's elaboration based on [16].

SUPPLY and CONSUMPTION	**Biomass**	**Charcoal**	*gasoline*	*AV fuel*	*Kerosene (JetA1 + AVgas)*	*Diesel*	*Fuel Oil*	*LPG*	**Electricity**	**Oil products**	**Total**
Production	16884.152	-	-	-	-	-	-	-	222.568	-	17106.720
Imports	-	-	*300.041*	*92.579*	*63.550*	*582.576*	*45.501*	*6.172*	0.000	1090.419	1090.419
Exports	-	-	-	-	-	-	-	-	7.654	-	7.654
TPES	**16884.152**	-	*300.041*	*92.579*	*63.550*	*582.576*	*45.501*	*6.172*	**230.222**	**1090.419**	**18204.793**
TPES (percentage)	**92.7%**	-	*1.6%*	*0.5%*	-	*3.2%*	-	-	**1.3%**	**6.0%**	**100%**
Charcoal/Elec.Production	-6875.551	687.555	-	-	-	*-253.283*	*-3.857*	-	77.142	-257.140	-6367.994
Prod+Transf+Distr.Losses	-476.600	-32.741	*-14.288*	*-4.409*	*-3.026*	*-27.742*	*-2.167*	*-0.294*	-65.962	-51.926	-627.229
TFC	**9532.001**	**654.814**	*285.753*	*88.170*	*60.524*	*301.551*	*39.477*	*5.878*	**241.402**	**781.353**	**11209.570**
TFC (percentage)	**85.0%**	**5.8%**	*2.5%*	*0.8%*	*0.5%*	*2.7%*	*0.4%*	*0.1%*	**2.2%**	**7.0%**	**100%**
Residential	7083.486	439.313	-	-	*54.472*	-	-	*4.702*	55.365	59.174	7637.338
Industry	1115.273	-	-	-	-	*66.341*	*39.477*	*1.176*	156.193	106.994	1378.460
Transport	-	-	*285.753*	*88.170*	*0.000*	*205.055*	-	-	-	578.978	578.978
Others	1333.242	215.501	-	-	*6.052*	*30.155*	-	-	29.844	36.207	1614.794
Commercial	1333.242	*215.501*	-	-	*6.052*	*0.000*	-	-	29.844	6.052	1584.639
Agricolture	-	-	-	-	-	*30.155*	-	-	0.000	30.155	30.155
TFC	**9532.001**	**654.814**	***285.753***	***88.170***	***60.524***	***301.551***	***39.477***	***5.878***	**241.402**	**781.353**	**11209.570**
TFC (percentage)	**85.0%**	**5.8%**	*2.5%*	*0.8%*	*0.5%*	*2.7%*	*0.4%*	*0.1%*	**2.2%**	**7.0%**	**100%**

Appendix B

Case studies data



QUOTE TO: **Mr/Mrs. Name** **Date:** **27/2/14**

7A Market Rise
Off Namuwongo Road.
Kampala, Uganda
Office : 0754363749
Phone : 0754880565/0757109902
www.villageenergyuganda.com

For:

APPLIANCES	NUMBER	POWER [W]	HOURS	PRICE [UGX]
LED Bulbs	8	40	6	120,000.00
Security Lights	4	20	12	60,000.00
Laptop	2	100	5	-
Phone charging	2	10	4	-
20" TV	1	100	4	-
Fridge	1	300	7	-
Standing Fans	1	50	4	-

You need:

APPLIANCES	TYPE	NUMBER	RATING	PRICE [UGX]
Panel [Watts]	Monocrystalline	4	240	3,360,000.00
Battery [Ah]	Lead-Acid ABM	2	200	1,900,000.00
Charge Controller [A]	40 AMP ASE	1	40	200,000.00
Inverter	1000 W Genesis	1	1000	1,000,000.00
Wall switch	-	9	Pieces	18,000.00
Lamp holders	-	12	Pieces	24,000.00
Wire 12mm MediumPanel	-	15	Metres	52,500.00
Wire 2.5mm house	-	20	Metres	40,000.00
Wire 1.5mm house	-	100	Metres	95,000.00
Wire 6mm BigBattery	-	10	Metres	50,000.00
Breaker box	-	1	Pieces	27,000.00
Breaker	-	2	Pieces	24,000.00
Clips 1.5mm	-	3	Packets	10,500.00
Clips 2.5mm	-	1	Packets	4,000.00
Battery connector	-	4	Pieces	4,000.00
Boundax	-	1	Piece	5,000.00
Tranking	-	12	Pieces	54,000.00
Flush plugs	-	1	Packets	3,500.00
screws wood	-	1	Packet	3,500.00
Molded boxes	-	16	Pieces	32,000.00
Brackets	-	16	Pieces	66,666.67
Wall sockets	-	7	Pieces	35,000.00
Top plug	-	7	Pieces	35,000.00
Timer	-	1	Piece	100,000.00
LABOUR			UGX	-
TOTAL			UGX	7,324,000.00

Please Note:

1. The quote is valid for the next 14 days.

2. Installation Commences on 70% down payment and the balance is payable at completion of the installation.

3. The battery has a six month guarantee.

4. The panels here also have a 1 year Guarantee.

5. The quote includes installation costs.

6. The quote don't include transport costs.

7. Quote doesn't include variations in lenght of wires. In case of changes in distance covered by wire quote shall subjected to change.

For Village Energy

THANK YOU FOR YOUR BUSINESS!!

Fig B.0.1 Typical printed Quotation of the *VE Sizing&Pricing* Tool.

Table B.0.1 Battery sizes list.

Total Battery Capacity [Ah]	Battery Rated Capacity [Ah]	Number	Price [UGX]
5	5	1	25,000.00
7	7	1	45,000.00
18	18	1	85,000.00
24	24	1	145,000.00
40	40	1	220,000.00
50	50	1	320,000.00
70	70	1	380,000.00
75	75	1	420,000.00
100	100	1	450,000.00
150	150	1	790,000.00
200	200	1	950,000.00
300	150	2	1,501,000.00
400	200	2	1,805,000.00
450	150	3	2,251,500.00
500	100	5	2,137,500.00
600	150	4	3,002,000.00
800	200	4	3,610,000.00

Table B.0.2 Charge controllers list.

Charge Controller Type	Rated current [A]	Price [UGX]
5 AMP Catalyst Pro	5	35,000.00
5 AMP Steca	5	90,000.00
10 AMP Catalyst Pro	10	60,000.00
20 AMP ASE	20	130,000.00
30 AMP ASE	30	150,000.00
30 AMP Steca	30	600,000.00
40 AMP ASE	40	200,000.00
40 AMP ProPower	40	900,000.00
80 AMP Outback	80	1,500,000.00

Table B.0.3 Part of the “other components” pricing list.

Components	Unit Price [UGX]	Number	Rating	Wholesales [UGX]
Battery connector	1,000.00	1	Piece	-
Brackets	4,166.67	12	Pieces	50,000.00
Breaker	12,000.00	1	Piece	-
Clips 1.5mm	3,500.00	1 of 100	Packet	-
Clips 2.5mm	4,000.00	1 of 100	Packet	-
Installation tape	1,000.00	1	Piece	-
Lamp holders	2,000.00	1	Piece	-
Moulded boxes	2,000.00	1	Piece	-
Panels stand (100W)	75,000.00	1	Piece	-
Screw metal	10,000.00	1 of 70	Packet	-
Top plug	5,000.00	1	Piece	-
Tracking	4,500.00	1	Piece	-
Wall sockets	5,000.00	1	Piece	-
Wall switch	2,000.00	1	Piece	-
Wire 1.5mm	950.00	100	Metres	95,000.00
Wire 2.5mm	2,000.00	100	Metres	200,000.00
Wire 6mm	5,000.00	90	Metres	450,000.00
Wire Earth	14,000.00	50	Metres	700,000.00

Table B.0.4 Case study, *Pricing sheet* results.

Components	Type	No./Qty	Rating	Unit cost [UGX]	Total cost [UGX]
PRINCIPAL COMPONENTS					
Panel [W]	Monocrystalline	4	240	840,000.00	3,360,000.00
Battery [Ah]	Lead-Acid ABM	2	200	950,000.00	1,900,000.00
Charge Controller [A]	40 AMP ASE	1	40	200,000.00	200,000.00
Inverter	1000 W Genesis	1	1000	1,000,000.00	1,000,000.00
Sub-Total Principal components [UGX]					6,460,000.00
DEVICES					
LED Bulbs		8	Pieces	15,000.00	120,000.00
Security Lights		4	Pieces	10,000.00	40,000.00
Laptop		2	Pieces	-	-
Phone charging		2	Pieces	-	-
20" TV		1	Pieces	-	-
Fridge		1	Pieces	-	-
Standing Fan		1	Pieces	-	-
Sub-Total Devices [UGX]					160,000.00
OTHERS COMPONENTS					
Wall switch		9	Pieces	2,000.00	18,000.00
Lamp holders		12	Pieces	2,000.00	24,000.00
Wire 12mm		15	Metres	3,500.00	52,500.00
Wire 2.5mm		20	Metres	2,000.00	40,000.00
Wire 1.5mm		100	Metres	950.00	95,000.00
Wire 6mm		10	Metres	5,000.00	50,000.00
Breaker box		1	Pieces	27,000.00	27,000.00
Breaker		2	Pieces	12,000.00	24,000.00
Clips 1.5mm		3	Packets	3,500.00	10,500.00
Clips 2.5mm		1	Packets	4,000.00	4,000.00
Battery connector		4	Pieces	1,000.00	4,000.00
Boundax		1	Piece	5,000.00	5,000.00
Tracking		12	Pieces	4,500.00	54,000.00
Flush plugs		1	Packets	3,500.00	3,500.00
Screws wood		1	Packet	3,500.00	3,500.00
Moulded boxes		16	Pieces	2,000.00	32,000.00
Brackets		16	Pieces	4,166.67	66,666.67
Wall sockets		7	Pieces	5,000.00	35,000.00
Top plug		7	Pieces	5,000.00	35,000.00
Timer		1	Piece	100,000.00	100,000.00
Sub-Total Others components [UGX]					683,666.67
Total Cost of goods [UGX]					7,323,666.67

Table B.0.5 Class types collected data list.

CLASS TYPE	**N_U**	**APPLIANCE NAME**	**P[W]**	**N_{App}**	**h_{funct}**	**N_{Win}**	**W_1**		**W_2**		**W_3**		**h_w**
Family_1	**50**	Lights (normal)	3	4	6	2	0	2	17	24	0	0	9
		Phone Charger	5	2	3	3	0	9	13	15	17	24	18
		Security Light	5	1	12	2	0	7	17	24	0	0	14
Family_2	**15**	Lights (normal)	3	4	6	2	0	2	17	24	0	0	9
		Phone Charger	5	2	3	3	0	9	13	15	17	24	18
		Security Light	5	1	12	2	0	7	17	24	0	0	14
		Radio	5	1	4	2	6	9	17	24	0	0	10
		AC-TV (small)	100	1	5	2	11	15	17	24	0	0	11
Family_3	**15**	Lights (normal)	3	8	6	2	0	2	17	24	0	0	9
		Phone Charger	5	2	3	3	0	9	13	15	17	24	18
		Radio	5	1	4	2	6	9	17	24	0	0	10
		Security Light	5	2	12	2	0	7	17	24	0	0	14
		AC-TV (small)	100	1	5	2	11	15	17	24	0	0	11
		Fridge (small)	250	1	5	1	0	24	0	0	0	0	24
Family_4	**10**	Lights (normal)	3	12	6	2	0	2	17	24	0	0	9
		Phone Charger	5	4	3	3	0	9	13	15	17	24	18
		Radio	5	1	4	2	6	9	17	24	0	0	10
		Security Light	5	4	12	2	0	7	17	24	0	0	14
		AC-TV (small)	100	1	5	2	11	15	17	24	0	0	11
		Standing Fan	55	1	6	1	8	24	0	0	0	0	16
		Decoder	15	1	5	2	11	15	17	24	0	0	11
		Fridge (small)	250	1	5	1	0	24	0	0	0	0	24
		Internet Router	20	1	6	1	0	24	0	0	0	0	24
		Laptop (small)	55	1	6	3	0	2	11	15	17	24	13
Family_5	**5**	Lights (normal)	3	16	6	2	0	2	17	24	0	0	9
		Phone Charger	5	4	3	3	0	9	13	15	17	24	18
		Radio	5	2	4	2	6	9	17	24	0	0	10
		Security Light	5	6	12	2	0	7	17	24	0	0	14
		AC-TV (big)	200	1	6	2	11	15	17	24	0	0	11
		Standing Fan	55	2	6	1	8	24	0	0	0	0	16
		Decoder	15	1	6	2	11	15	17	24	0	0	11
		Fridge (big)	400	1	5	1	0	24	0	0	0	0	24
		Internet Router	20	1	8	1	0	24	0	0	0	0	24
		Laptop (big)	80	2	8	3	0	2	11	15	17	24	13
Family_6	**5**	Lights (normal)	3	16	6	2	0	2	17	24	0	0	9
		Phone Charger	5	4	3	3	0	9	13	15	17	24	18
		Radio	5	2	4	2	6	9	17	24	0	0	10
		Security Light	5	6	12	2	0	7	17	24	0	0	14
		AC-TV (big)	200	1	6	2	11	15	17	24	0	0	11
		Standing Fan	55	2	6	1	8	24	0	0	0	0	16
		Decoder	15	1	6	2	11	15	17	24	0	0	11
		Fridge (big)	400	1	5	1	0	24	0	0	0	0	24
		Internet Router	20	1	8	1	0	24	0	0	0	0	24
		Laptop (big)	80	2	8	3	0	2	11	15	17	24	13
		Hair Dryer	1000	1	0.5	1	17	24	0	0	0	0	7
		Printer	50	1	0.5	1	17	24	0	0	0	0	7
		Stereo	100	1	3	1	17	24	0	0	0	0	7
		Water Heater	660	1	2	2	0	2	18	24	0	0	8
Enterprise_1	**15**	Fluor. Tube (small)	36	10	6	2	7	11	16	20	0	0	8
		Phone Charger	5	4	3	2	7	13	15	20	0	0	11
		Security Light	5	4	12	2	0	7	17	24	0	0	14
		Internet Router	20	1	10	1	7	20	0	0	0	0	13
		Laptop (big)	80	1	8	2	7	13	15	20	0	0	11
		Laptop (small)	55	5	8	2	7	13	15	20	0	0	11
		Printer	50	2	2	2	7	13	15	20	0	0	11
		Standing Fan	55	2	8	2	7	13	15	20	0	0	11
Enterprise_2	**5**	Fluor. Tube (big)	47	20	6	2	7	11	16	20	0	0	8
		Phone Charger	5	15	3	2	7	13	15	20	0	0	11
		Security Light	5	10	12	2	0	7	17	24	0	0	14
		Internet Router	20	1	10	1	7	20	0	0	0	0	13
		Laptop (big)	80	5	8	2	7	13	15	20	0	0	11
		Laptop (small)	55	10	8	2	7	13	15	20	0	0	11
		Standing Fan	55	5	8	2	7	13	15	20	0	0	11
		Water dispenser	550	1	3	2	7	13	15	20	0	0	11
		Photocopier	750	1	1	2	7	13	15	20	0	0	11
		Ceiling Fan	75	5	8	2	7	13	15	20	0	0	11
		PC	400	1	10	1	7	20	0	0	0	0	13

Mobile Money	**5**	Lights (normal)	3	2	3	2	8	11	16	20	0	0	7
		Phone Charger	5	3	3	1	8	18	0	0	0	0	10
		Standing Fan	55	1	6	1	10	18	0	0	0	0	8
Kiosk	**10**	Lights (normal)	3	2	3	2	8	11	16	20	0	0	7
		Phone Charger	5	1	3	1	8	18	0	0	0	0	10
		Standing Fan	55	1	6	1	10	18	0	0	0	0	8
		Fridge (small)	300	1	8	1	0	24	0	0	0	0	24
		Fridge (big)	500	1	8	1	0	24	0	0	0	0	24
Barber	**2**	Lights (normal)	3	5	8	2	8	13	15	20	0	0	10
		12V shaver	10	5	6	2	8	13	15	20	0	0	10
		Ceiling Fan	75	3	8	2	8	13	15	20	0	0	10
		UV sterylizer	50	1	2	2	8	13	15	20	0	0	10
Tailor	**3**	Lights (brighter)	5	3	8	2	8	13	15	20	0	0	10
		Sewing machine	50	1	3	2	8	13	15	20	0	0	10
		Ceiling Fan	75	1	8	2	8	13	15	20	0	0	10
Market Place	**1**	Lights (normal)	3	25	3	2	8	11	16	20	0	0	7
		Security Light	5	25	12	2	0	7	17	24	0	0	14
		Fridge (small)	300	3	8	1	0	24	0	0	0	0	24
		Fridge (big)	500	3	8	1	0	24	0	0	0	0	24
		Standing Fan	55	10	8	2	8	13	15	20	0	0	10
		Radio	5	10	4	2	10	13	15	18	0	0	6
Club	**3**	Fluor. Tube (small)	36	10	8	2	0	4	17	24	0	0	11
		Fluor. Tube (big)	47	5	8	2	0	4	17	24	0	0	11
		Security Light	5	5	12	2	0	7	17	24	0	0	14
		Phone charger	5	10	8	1	15	24	0	0	0	0	9
		AC-TV (small)	130	2	9	2	0	4	15	24	0	0	13
		AC-TV (big)	200	1	9	2	0	4	15	24	0	0	13
		PC	400	1	9	2	0	4	15	24	0	0	13
		Laptop (big)	80	10	6	1	15	24	0	0	0	0	9
		Printer	50	1	1	1	15	20	0	0	0	0	5
		PicoProjector	18	1	4	2	0	2	20	24	0	0	6
		Amplyfier	6	1	4	2	0	2	20	24	0	0	6
		Ceiling Fan	75	3	8	2	0	4	15	24	0	0	13
		Music System	178	1	8	2	0	4	15	24	0	0	13
		Internet Router	20	1	9	2	0	4	15	24	0	0	13
		Fridge (small)	300	2	8	1	0	24	0	0	0	0	24
		Fridge (big)	500	1	8	1	0	24	0	0	0	0	24
Street Lights	**1**	Lights (Street)	50	100	12	2	0	7	17	24	0	0	14
		Led strips	8	100	12	2	0	7	17	24	0	0	14
Primary School	**1**	Fluor.Tube (small)	36	10	4	1	8	17	0	0	0	0	9
		Phone Charger	5	7	3	1	8	17	0	0	0	0	9
		Security Light	5	4	12	2	0	7	17	24	0	0	14
Pharmacy	**1**	Lights (normal)	3	10	3	2	8	11	16	20	0	0	7
		Security Light	5	4	12	2	0	7	17	24	0	0	14
		Fridge (small)	300	3	8	1	0	24	0	0	0	0	24
		Fridge (big)	500	2	8	1	0	24	0	0	0	0	24
		Standing Fan	55	3	8	2	8	13	15	20	0	0	10

List of Acronyms and Symbols

Acronyms

AC	Alternate Current
AM	Air Mass
BOS	Balance of Systems
CD	Cloudy-Days
CF	Cash Flow
CRF	Capital Recovery Factor
DC	Direct Current
DOD	Depth of Discharge
EXC	Exchange rate
LC	Life Cycle
LCOE	Levelized Cost Of Energy
LHV	Lower Heating Value
LL	Loss of Load
LLP	Loss of Load Probability
LPV	Loss Photovoltaic (energy)
LPVP	Loss Photovoltaic (energy) Probability
MMP	Maximum Power Point
MPPT	Maximum Power Point Tracker
NOCT	Nominal Operation Cell Temperature
NPC	Net Present Cost
NPR	Net Present Revenue
O&M	Operation and Maintenance
OC	Open Circuit
PSH	Peak Sun Hours
PV	Photovoltaic
PWM	Pulse Width Modulator
SAPV	Stand-Alone Photovoltaic
SC	Shirt Circuit
SHS	Solar Home System
SOC	State of Charge
UPV	Useful Photovoltaic (energy)
VE	Village Energy

Symbols

App	Appliances
b	Battery, Single
Bat	Battery, Bank
C	Capacity
CH	Charge

d	Daily
$DISCH$	Discharge
E	Energy
EE	Electrical Energy
$Funct$	Functioning
G	Irradiance
h	Nominal Irradiance
H	Irradiation
h	Hour
I	Current
i	Ith-device
Inv	Inverter
L	Load
Lgt	Lighting
m	Month
Mod	Module
N	Number of Device ith
n	Night
obj	Objective
p	Peukert Constant
P	Power
Ph	Phone Charging
r	Real Interest Rate
St	String
Sys	System
t	Time-step
T	Temperature
$thrpt$	Annual Throughput of battery
US	Users
V	Voltage
Win	Window
z	Charge/Discharge Cycles at a chosen DOD
β	Tilt Angle
η	Efficiency
P	Coefficient of Power

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