A Concept of Dynamic Pricing for Rural Hybrid Electric Power Mini-Grid Systems for Sub-Saharan Africa

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***Abstract*-- This paper presents a dynamic pricing concept that can be applied to hybrid electric power mini-grid systems to enable affordability of energy in these systems setup for the supply of energy to rural consumers. A location was identified in Eastern Uganda, resource assessment done, and a proposed hybrid electric power mini-grid system designed to supply electricity to this rural location. A theoretical deterministic demand profile was generated, and with it different supply configurations of the system were simulated to meet the daily load. The fluctuations in the demand and supply triggered a change in the cost of generating energy, due to the variations in the contributing electricity generating sources.**

Through communication, an intelligently designed and operated time-varying pricing scheme can be an effective tool for influencing the actions of price-responsive end-users such as rural consumers. A software program was used to simulate the hourly demand, supply, and corresponding cost of energy variations. This pricing model could potentially contribute to the ongoing search for the provision of affordable rural energy services.

***Key words*-- Rural electrification, Renewable Energy, Hybrid mini-grid systems, smart grid, tariff, real-time pricing**

I. Introduction

Rural electrification in sub-Saharan Africa has progressed at extremely slow rates. This is attributed mainly to the expense associated with either extending the electricity grid, or setting up isolated mini-grid systems to supply electricity to these areas [1].Initially low capital costs had often favored diesel generators for mini-grid applications, but recent instabilities in the price and availability of fuel, high maintenance and life cycle cost of diesel generators, and the associated pollution, has warranted a shift towards renewable energy technologies [2]. However, due to the intermittence of renewable resources, and the additionally high capial costs of renewable technologies, stand-alone renewable energy systems can be infeasible for rural electrification, thus hybrid mini-grid systems are designed to incorporate both renewable and conventional generator technologies. These systems have the potential to offer clean and sustainable energy for rural electrification in sub-Saharan Africa [3].

However, recent applications in sub-Saharan Africa have not found the expected success. Recent pilot projects in South Africa at the Hluleka Nature Reserve, and a replica at Lucingweni village in the Eastern Cape Province, both experienced a problematic lifetime which eventually led to their collapse [4]. On the other hand, the Ugandan governments continued strive for rural electrification has led to the implementation of a number of mini-grid systems over the last decade. Mostly based on diesel generators, the majority of these systems have gone on to fail due to high fuel costs, consumer dissatisfaction and mismanagement [5].

One of the major huddles for setting up mini-grid systems is the cost of energy. Given that these systems are usually setup for the supply of rural consumers; their sustainability and economic viability provides a challenge for the governments and independent power producers [1].Tariff setting in electrification project is one of the most important elements of rural electrification. Utilities face a challenge on how to fairly allocate the operating costs while calculating a reasonable tariff for the end-use consumer [6].

The elements of the end user tariff as modeled for most grid or mini-grid systems normally comprise; a fixed standing charge (cost per month), an energy charge (cost per KWh of energy consumed) and a capacity charge (demand charge to cater for consumers who utilize peak generators to meet their demand)[7]. The fixed charge considers capital and maintenance costs that are not related to operation, while the energy charge is a variable price that considers the costs that are related to the operation (wear out, fuel, maintenance) of the system [8]. Usually for grid systems, end-user customers are billed by utilities based on subdivisions into domestic, commercial or industrial loads. Domestic consumers incur a flat-rate tariff based on the fixed charge and the energy charge, while commercial and industrial consumers include a capacity charge for time-of-use consumption due to the peak demand they impose on the generation system, necessitating additional capacity [7].

Tariff structuring in mini-grid systems has seen the energy utility impose a flat-rate electricity charge based on calculations done through the fixed cost and the energy charge, irrespective of the generator composition, time of use or season [9]. Although most rural customers are willing to

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pay for the energy service, their ability is financially limited, and the tariff they can afford is not usually enough to reflect the actual system costs and make the investment profitable.

Therefore, there's need for innovation in ways to make mini-gird systems financially viable and sustainable in the long run. A dynamic pricing model offers an alternative approach for tariff setting in rural hybrid electric power mini-grid systems. This can potentially improve affordability of energy services for rural consumers. Other support mechanisms in the form of funding that have been proposed for the support of renewable energy technologies for rural electrification are discussed below.

II. FUNDING MINI-GRID SYSTEMS

The installation of mini-grid systems in isolated rural areas has always involved some form of government or donor subsidy to front the initial capital investment [2]. Given that tariffs paid by users in rural communities are not usually enough to cover the initial capital and generating cost, alternative funding mechanisms have always been a fixture in the setup of mini-grid systems for rural supply.

Currently, proposed funding schemes promote the utilization of renewable energy technologies in hybrid mini-grid systems, for rural electrification. Some of the new funding concepts that have been proposed are summarized below.

A. The Renewable Energy Premium Tariff (RPT)

The RPT is a variation of the Renewable Energy Feed-in-Tariff (REFiT). The REFiT has been a successful mechanism in increasing the deployment of renewable energy technologies in grid-connected systems [15]. The RPT is a locally adapted variation of the REFiT scheme which pays for the renewable electricity generated; to encourage the production of electricity using renewable technology based mini-grids in developing countries [2].

The RPT is a financial scheme designed to help offset the high capital costs associated with most renewable energy projects. Different possible structures are discussed by [2] for the implementation of RPTs in village-grid electrification projects. The RPT's aim is to achieve different economic purposes such as affordability for local users, to achieve a return of investment, and to generate earnings for energy service companies [2].

B. The Global Energy Transfer Feed-in-Tariff (GETFiT)

The GET-FiT program is a concept designed to support the development of renewable energy projects in the developing world through the creation of international public-private partnerships. In this set-up, international AAA-rated donors such as national governments, development banks, and international climate-related funds, contribute premium payments for renewable energy projects in partnership with developing country governments [10].

This program serves as a bridge to grid parity for renewable energy, both by allowing developing countries to gain experience with renewable resources and technologies prior to break-even scenarios, and by adjusting incentive rates to reflect lower prices over time [10].

This scheme de-risks the investors and can establish fair and sufficient returns. Developing countries' governments and utilities administer the process and guarantee to pay generators at a rate based on the avoided cost of fossil fuel generation. This will then lead to private investors deploying capital in renewable energy projects [10].

C. Tradable Certificates

In order to reduce greenhouse gases and mitigate the effects of climate change, countries around the world are encouraging companies to cut down their carbon emissions. The concept of carbon trading involves the transfer of credits, through a direct correlation between carbon emissions and revenue. A carbon credit is equivalent to one metric tonne of CO_2 emitted [11]. Hence, a limit or a cap on the amount of carbon emission is put on its companies by a country. Therefore, the companies that need to increase their emissions have to buy credits from those who pollute less, or from green (renewable) technology projects. Thus, recent policy measures in several countries aim to encourage renewable energy generation through tradable certificates or carbon credits [11].

Under this umbrella, small-scale renewable energy systems for remote area power supply, that rely on solar photovoltaic, wind turbine, and small hydro technologies for their renewable energy input are eligible for creating Renewable Energy Certificates, and consequently give rise to an instrument that may then be traded on a market [12].

Smart-grid technology offers the next step in improving the affordability of hybrid mini-grid systems for rural electrification.

III. DYNAMIC PRICING

Tariff prices that vary several times a day create opportunities for price-responsive customers to participate in demand side management opportunities, so as to save money. Dynamic pricing schemes represent time-varying, hourly-based electricity tariff scheme for end-users. These can be used to reflect the actual generation and transmission costs for a given period of electricity demand and supply [13]. Many variable tariff schemes are presently in application in different pricing models; these include various time-of-use pricing models currently utilized for industrial and commercial consumers on grid systems who utilize peak generation plants [14], real-time pricing models have been featured a lot recently in various publications especially on smart-grid technology and its applicability for grid systems.

The benefits of these pricing concepts range from achieving better operating efficiencies, to anticipating and avoiding service interruptions, and other operating problems [15]. The onus is thus to translate these smart concept to hybrid mini-grid systems for rural energy supply.

IV. CASE STUDY: WANALE VILLAGE

Wanale village is located in Mbale district, eastern Uganda at the coordinates 1.0210522N, 34.189341E. Many of the members in this community are subsistence farmers who rely on their produce for a source of income. Energy services are provided through local resources such as kerosene for lighting, and fuel wood for cooking [16]. It is situated 7Km from the nearest grid-electricity distribution line. The members of this community identified the potential to utilize the available hydro resources in the area for the generation of electricity to provide energy services to their people. A feasibility study was done by Micro Power Uganda ltd, and a project design and costing established for the proposed Pico-hydro power plant.

In this study, based on the foundation of the hydro resources, a hybrid mini-grid system is designed for this location to also incorporate the available solar resources, with a diesel generator, battery storage and inverter included as part of a back up and energy storage system.

Solar radiation data is generated from the NASA website (coordinates 1.0210522N, 34.189341E) as shown in Fig 1 [17].

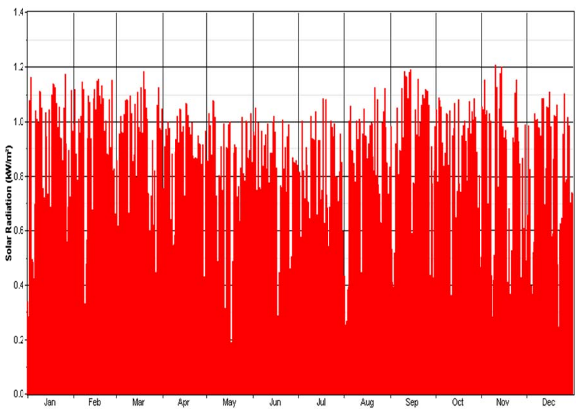

Fig. 1: Solar irradiation data for Wanale

This system design is sized and optimized in NREL's HOMER software as in Fig 2,to supply electricity to this remote location,and is used to investigate the hourly supply options for the village [18].

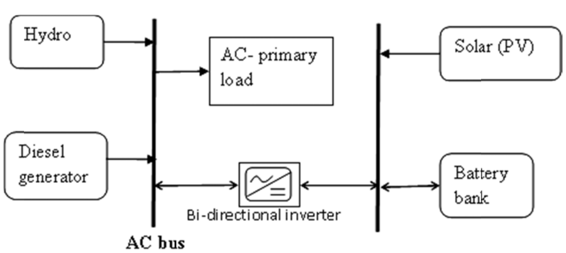

Fig.2: Hybrid power system configuration

A. Demand Profile

A theoretical rural load is generated, based on an estimate of a 24 hour consumption pattern of the 80 households in Wanale village. The loads are derived from work done by [19], for estimating electricity demand in rural villages in Tanzania.

The generic load profiles include:

- A typical rural residential load profile with consumption based on an assumption of lighting and small household appliances such as a radio, a TV set for some, and a few consumers with fridges. Peak consumption is in the evening when all the lights and TV sets are switched on.
- A rural profile with day time commercial activity. This is derived from the assumption of the presence of small businesses in the trading centre, such as shops, restaurants, bars, video show centres, charging stations, a fuel pump, and a dispensary.

A total load profile is then generated combining the residential and commercial consumptions, to represent Wanale's daily load profile. A 72hour demand profile is thus simulated as shown in Fig 3.

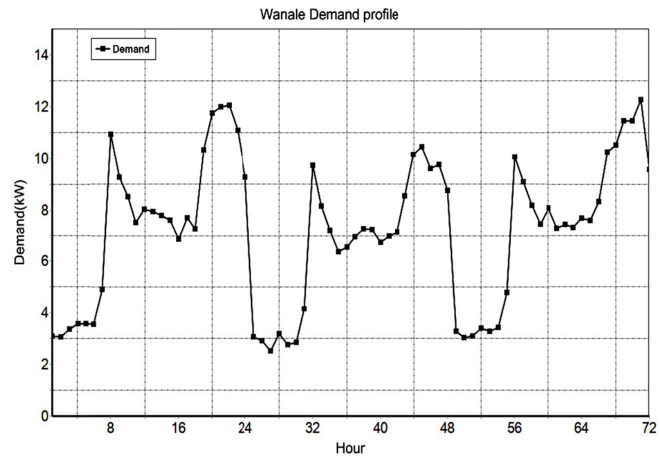

Fig. 3: Wanale load profiles

B. Supply scenarios

HOMER software is used to size, optimize and simulate the supply configurations for meeting the daily load. HOMER's algorithm for calculating the Life cycle costs and thus the corresponding Levelized Cost of Energy (LCOE) is based on the formula below:

$$LCOE = \frac{C_{ann,total} - C_{boiler}E_{thermal}}{E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales}}$$

Where;

$C_{ann,total}$= total annualized cost of the system [$/yr]

C_{boiler} =boiler marginal cost [$/kWh]

$E_{thermal}$ = total thermal load served [kWh/yr]

$E_{prim,AC}$ = AC primary load served [kWh/yr]

$E_{prim,DC}$ = DC primary load served [kWh/yr]

E_{def} = deferrable load served [kWh/yr]

$E_{grid,sales}$ = total grid sales [kWh/yr]

Thus, the electricity price is the Cost of Energy (COE) in $/kWh that makes Costs = Revenues:

The optimal system in HOMER is simulated to comprise a 4.4kW supply from hydro, a 7kW PV array supply, a 5kW bi-directional inverter, a 5kW diesel backup generator and a 15unit battery bank (Absorbent glass mat (AGM) sealed deep-cycle lead-acid battery.) energy storage facility with 57.6kWh nominal capacity.

The simulated hybrid supply system is further analyzed through HOMER's hourly output simulations.

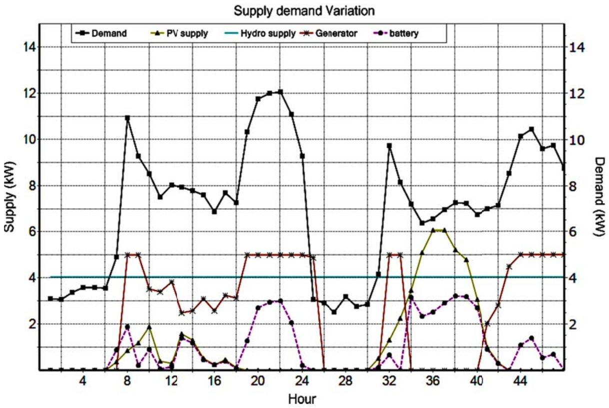

Fig. 4: Wanale total optimized demand and supply for 48h

As observed in Fig 4, hydro power provides the base load supply of electricity, with hourly input from the battery storage, PV, and the diesel generator to contribute to the supply when the need for extra power arises. Thus, as observed, different generation topologies contribute to the electricity supply during different parts of the day depending on the load.

C. Cost of Energy

The HOMER optimized cost of energy output for the hybrid mini-grid system is **$US 0.301/kWh**; this corresponds to an initial cost of **$US 51,979**and a Life Cycle Cost of **$US 207,685**.

Thus, at a demand of **69,450kWh/yr**; the total energy cost for Wanale village is:

69,450 × 0.301 = $US 20904.45/yr

Thus the Village of Wanale pays $US1742.38/month

For an approximate number of 80 households, the monthly tariff for each household = **$ 21.8**

This cost of energy represents a supply situation in which all the generators are contributing to the electricity supply to meet village demand. But as observed in fig 4, this situation arises for only certain periods of the day. And given that the different technologies in the hybrid mini-grid configuration generate electricity at different individual costs, the hourly variations in the contributing generation sources should also result in a variable cost of energy throughout the day. By simulating the sized hybrid mini-grid system in HOMER at different capacity constraints, the designed system can be simulated to establish the cost of energy variation with the different supply configurations.

Thus the hourly fluctuations in the supply-demand and the corresponding cost of energy are established as shown in Table 1.

Table 1: Supply configurations and their corresponding cost of energy

Supply situation	COE ($/kWh)
Hydro + PV + diesel + battery	0.301
Hydro + diesel + battery	0.348
Hydro + PV + battery	0.148
Hydro + battery	0.115
Hydro	0.034

Thus the cost of energy variation with supply and demand over a period of 72hours, and 1 month is as shown in the figures 5 and 6.

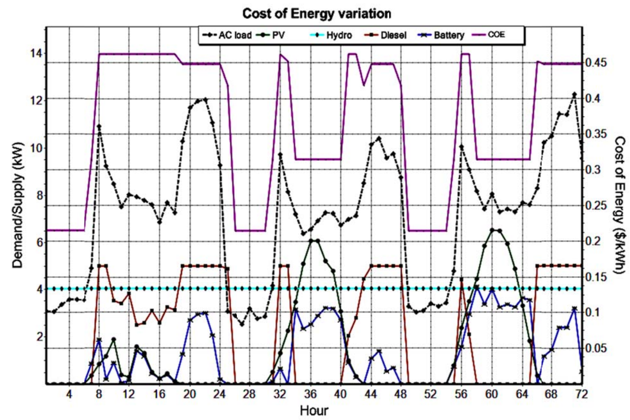

Fig.5: Cost of Energy variations over 72h

As shown in the Fig 5, the time of day when the only contributing generation source is hydro corresponds to the least energy cost, and as other supply sources are dispatched to cater for the extra demand, the cost of energy also rises. Thus the cost of energy will fluctuate according to the contributing energy source, with the higher cost of energy analogous to the periods of the day when all the generators are contributing to the energy supply.

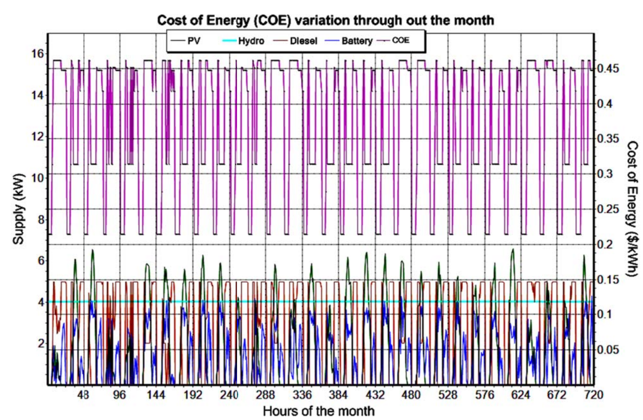

Fig.6: Cost of Energy variations for a period of 1 month

These cost variations are not reflected in a flat-rate electricity charge, and do not reflect the actual demand-supply-cost situation throughout the day. A dynamic pricing scheme applied to such a system can result in significant cost savings.

By considering these hourly cost changes, and taking the average COE, the corresponding COE = **$0.189/kWh**

Thus, at a demand of **69,450kWh/yr**; the total energy cost for Wanale village is:

69,450 × 0.189 = $13,139.9/yr

Thus the Village of Wanale pays $1,095/month

For an approximate number of 80 households, the monthly tariff for each household =**$ 13.69**

In table 2, a cost comparison is made to evaluate the savings potential and/ feasibility of the dynamic pricing scheme as compared to the fixed charge. The variations in the cost of energy should lead to significant saving on the demand side.

Table 2: Cost of energy comparisons

	Cost of Energy ($)	
	Fixed	Variable
KWh	0.301	0.189
Village/month	1,742.38	1,095
Village/year	20,904.45	13,139.9
COE/month/household	21.8	13.69
Difference/village savings per year	**$ 7,764.55**	
Household savings per year	**$ 97.1**	

As shown in table 2, by comparison, significant cost savings of up to $0.112/kWh are derived from implementing a variable pricing system, corresponding to yearly savings of about $97 per household per year. Through a dynamic pricing scheme, the customers on the demand side have an economic incentive to react accordingly to the cost variations, thus further saving money.

V. ISSUES TO CONSIDER

The model discussed in this paper is a theoretical analysis of savings that could be obtained from a hybrid electric power mini-grid system utilizing a variable tariff structure. This tariff would respond to the variability in the availability of generation resources, thus reflecting the electricity supply situation. The implementation of such a model is not covered in the scope of this study.

Such a system would require the installation of smart metering technologies to monitor the supply situation of the various component generators, and a smart energy management system to correspond to the changing tariff calculations to the consumers. Such a model energy management system is presented in [21]. Automated Metering Infrastructure (AMI) would be necessary to allow real-time pricing signals to be shared between the utility and the customer, providing for a system in which consumers can adjust their energy consumption behaviors to periods when they could save money [22].

Such a setup though would significantly add to the cost of the system. But given that most rural electrification initiatives are usually subsidized by government or private funding mechanisms, the additional cost of the AMI could also be covered in the subsidies. This could also present an opportunity to test the applicability of smart technologies in rural electrification settings.

VI. CONCLUSIONS

Energy utilities have a responsibility of providing energy services to rural consumers in the most affordable way possible. A dynamic pricing scheme reflects a realistic supply situation of the hybrid mini-grid system. This way, consumers pay for their real energy consumption, reflecting the actual supply situation.

It is a fact that rural consumers are, by setting, poor customers. Though willing to pay for energy services, their ability to afford them is usually limited. Therefore, the installation of mini-grid systems for isolated rural communities always involves some form of government or donor intervention, to either front the whole or a percentage of the initial capital investment, as a form of fuel levy (in the case of generator run mini-grids), or to subsidize the cost of energy [2].Compared to the mini-grid tariff, the current electricity tariff for residential consumers connected to the grid in Uganda is Ush.385/kWh [20]. At a U.S$ exchange rate of Ush.2500 = $0.154/kWh.

Rural consumers are low income earners who are very sensitive to how they spend their hard earned money. Therefore, in order for hybrid electric power mini-grid systems to be sustainable in rural settings, a specialized tariff structure has to be designed, that takes into account what rural consumers can afford. And thus establish a sustainable funding structure for the system to include alternative funding mechanisms where necessary. A sustainable economic structure will ensure financial security and thus system longevity

A dynamic pricing scheme offers an alternative to the conventional flat rate electricity charge, as currently implemented by utilities. This way, the consumers are aware of the cost changes and can adjust their consumption to periods when they can save money.

This setup, in concert with funding mechanisms such as the Renewable energy Premium Tariff, the Global Energy Transfer Feed-in Tariff, renewable energy tradable certificates, and carbon credits, can establish a financially sustainable structure for the setup and operation of affordable hybrid mini-grid systems for rural electrification.

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