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A Feasibility and Implementation Model of Small-Scale Hydropower Development for Rural Electrification in South Africa: Design Chart Development

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***Abstract*—**Small scale hydropower used to play a very important role in the provision of energy to urban and rural areas of South Africa. The national electricity grid, however, expanded and offered cheap, coal generated electricity and a large number of hydropower systems were decommissioned. Unfortunately, large numbers of households and communities will not be connected to the national electricity grid for the foreseeable future due to high cost of transmission and distribution systems to remote communities due to the relatively low electricity demand within rural communities and the allocation of current expenditure on upgrading and constructing of new coal fired power stations. This necessitates the development of feasible alternative power generation technologies. A feasibility and implementation model was developed to assist in designing and financially evaluating small-scale hydropower (SSHP) plants. Several sites were identified using the model. The SSHP plants were designed for the selected sites and the designs for the different selected sites were priced using pricing models (civil, mechanical and electrical aspects). Following feasibility studies done on the designed and priced SSHP plants, a feasibility analysis was done and a design chart developed for future similar potential SSHP plant projects. The methodology followed in conducting the feasibility analysis for other potential sites consisted of developing cost and income/saving formulae, developing net present value (NPV) formulae, Capital Cost Comparison Ratio (CCCR) and levelised cost formulae for SSHP projects for the different types of plant installations. It included setting up a model for the development of a design chart for a SSHP, calculating the NPV, CCCR and levelised cost for the different scenarios within the model by varying different parameters within the developed formulae, setting up the design chart for the different scenarios within the model and analyzing and interpreting results. From the interpretation of the develop design charts for feasible SSHP in can be seen that turbine and distribution line cost are the major influences on the cost and feasibility of SSHP. High head, short transmission line and islanded mini-grid SSHP installations are the most feasible and that the levelised cost of SSHP is high for low power generation sites. The main conclusion from the study is that the levelised cost of SSHP projects indicate that the cost of SSHP for low energy generation is high compared to the levelised cost of grid connected electricity supply; however, the remoteness of SSHP for rural electrification and the cost of infrastructure to connect remote rural communities to the local or national electricity grid provides a low CCCR and renders SSHP for rural electrification feasible on this basis.

***Keywords*—**Feasibility, cost, rural electrification, small-scale hydropower.

I. INTRODUCTION

ALTHOUGH the electrification of urban areas in South Africa has reached great heights in recent years, including informal settlements within urban areas, there is still work to be done. The lack in provision of a reliable and sustainable electricity supply to rural communities within South Africa remains a problem. SSHP used to be vital in the electrification of urban and rural areas of South Africa. In South Africa, the concept of generating electricity using water turbines was first suggested in 1879 for lighting purposes in Cape Town [1] and Pretoria by using SSHP schemes. With the expansion of the national electricity grid, coal generated electricity become cheaper and subsequently hydropower stations were decommissioned in large numbers.

Since 2008 the parastatal, ESKOM, started experiencing numerous problems in managing the national electricity grid. The South African Government is committed to universal access to electricity across South Africa. The South African Electrification Programme has shifted its emphasis from the 80% electrified urban areas to the sparsely 45% electrified rural areas of South Africa [2]. The development of rural electrification however, remains unattended as ESKOM, since 2008, has been experiencing problems in supplying sufficient electricity to the users which are already connect to the local or national electricity grid. This being the result of a generation capacity shortage. The current coal-fired power stations and the existing major transmission and distribution lines, which form the primary electricity infrastructure within the urban areas, cannot sustain the supply of electricity against the demand of the existing users connected to the national electricity grid. Rural areas of South Africa are standing in the queue, behind already connected urban users, waiting for the national utility, ESKOM, to increase the margin between supply and demand generation. The capacity problem needs to be addressed along with the delays in electrification expansion development. The South African Government has an objective of universal access of energy generation and electricity to all

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its citizens. In order to achieve this objective, alternative energy technologies will not only need to be developed, but also implemented [3].

Small hydropower schemes can be pivotal in providing energy access to rural communties in South Africa. [4]. Numerous international installations have proven small hydro as among the best renewable energy technologies ideal for rural electrification or the supply of electricity to remote communities [5]. Water-scarcity in South Africa has threatened the viability of hydropower as a renewable source of energy. Even so, only a fraction of the potential available for hydropower has been exploited and the lack of explicit models on the sustainable generation and supply of energy using SSHP for South Africa further challenges the selection of hydropower as a viable source of energy. There is also a general lack of awareness of the prospects SSHP offers amongst local stakeholders [4].

The study encompassed the development of a feasibility and implementation model for assistance in the design of SSHP plants. The model was also developed to assist in the financial evaluation of SSHP plants. The model was incorporated into the development of feasibility and design charts for the evaluation and design of future SSHP plants for rural electrification in South Africa, and to raise awareness of the prospects SSHP offers amongst both local and international stakeholders.

II. IMPLEMENTATION MODEL

A model was designed and constructed for the feasible implementation of a SSHP project for rural electrification in South Africa. The model can also be implemented on international projects by varying cost equations and currencies to project and country specific values

The implementation model describes steps to be followed in identifying a technically possible and feasible opportunity to develop a SSHP site for rural electrification. The different sections within the model, based on the research and SSHP designs done, are outlined and explained in the subsequent sections of the article. Figs. 1-3 show the three different sections, namely Site Selection, SSHP and Cost, which combine to form the complete implementation model. Continuous referral from the sections to implications in either the preceding or subsequent sections of the implementation model provides a comprehensiveness to the model which allows for a sustainable implementation of the SSHP project from the conceptual phase to the commissioning of the plant.

III. SITE SELECTION AND DESIGNS

The implementation model was used to identify potential SSHP sites, select sites for implementation, and design SSHP plants at selected sites. This was done in order to prove the hypothesis that it is feasible and technically possible to provide small-hydropower installations for rural electrification in South Africa. From this focus, all the aspects related to the selection of suitable sites can be categorized into three categories, which by definition sums up the purpose and expected outcome of the study. These three categories are as:

1) Feasibility The feasibility of a project depends on two factors, the cost required and the valued obtained in incurring he cost. Some conduit hydropower projects might have a low cost compared to value obtained resulting in a fast payback period, while others may have the additional value of being able to service remote sites [6]. The same is true for SSHP projects. The feasibility of the installation depends on the ability of providing electricity to an end user at a lower unit cost that it would cost the Electricity Service Provider to provide infrastructure to supply the end users with electricity, i.e. to provide and installation, within a remote community which is not grid connected, at a cost similar to what it would take ESKOM to provide the infrastructure to connect the remote community to the grid.
2) Technical – the technical ability to develop a site to generate electricity by means of a SSHP depends mainly on the availability of flow and head. Different technologies are used for different combinations of head and flow available.
3) Rural – Rural in terms of the study was classified as any community not connected to the electricity grid and with no planning to be connected to the electricity grid in the near future. Rural will also include communities or individuals which are in close vicinity to the electrical grid yet cannot afford to purchase electricity from the Electricity Service Provider due to socioeconomic reasons.

All the parameters investigated or used for the selection of potential sites for the study is in one way or another related to the above mentioned three categories. Some sites might have the technical capacity to be developed but might be unfeasible due to large expenditure on infrastructure needed. Other sites might be feasible and technically possible yet contained within an urban area with a well-established electrical grid and infrastructure.

One of the several designed sites for the study is the Kwa Madiba SSHP plant within the Mhlontlo Local Municipality in the Eastern Cape Province of South Africa (31°11'38.15"S 29° 3'18.58"E).

The Thina Falls on the Thina River is in close proximity to the Kwa Madiba community in the Mhlontlo Local Municipality. The geometry and hydrology of the Thina Falls offered a feasible and viable opportunity for SSHP design and development. A flow rate of 640 ℓ/s is present within the Thina River at Thina Falls 95% of the time.

The maximum theoretical hydropower generation capacity at the Thina Falls was calculated as 350 kW, only taking into account flow present 95% of the time and not utilizing periodic flood peaks. Due to environmental and electricity generation legislation and regulatory aspects the plant was only designed for 50 kW power output utilizing a design flow rate of 150 ℓ/s. Table I shows an overview of the technical data of the Kwa Madiba SSHP scheme.

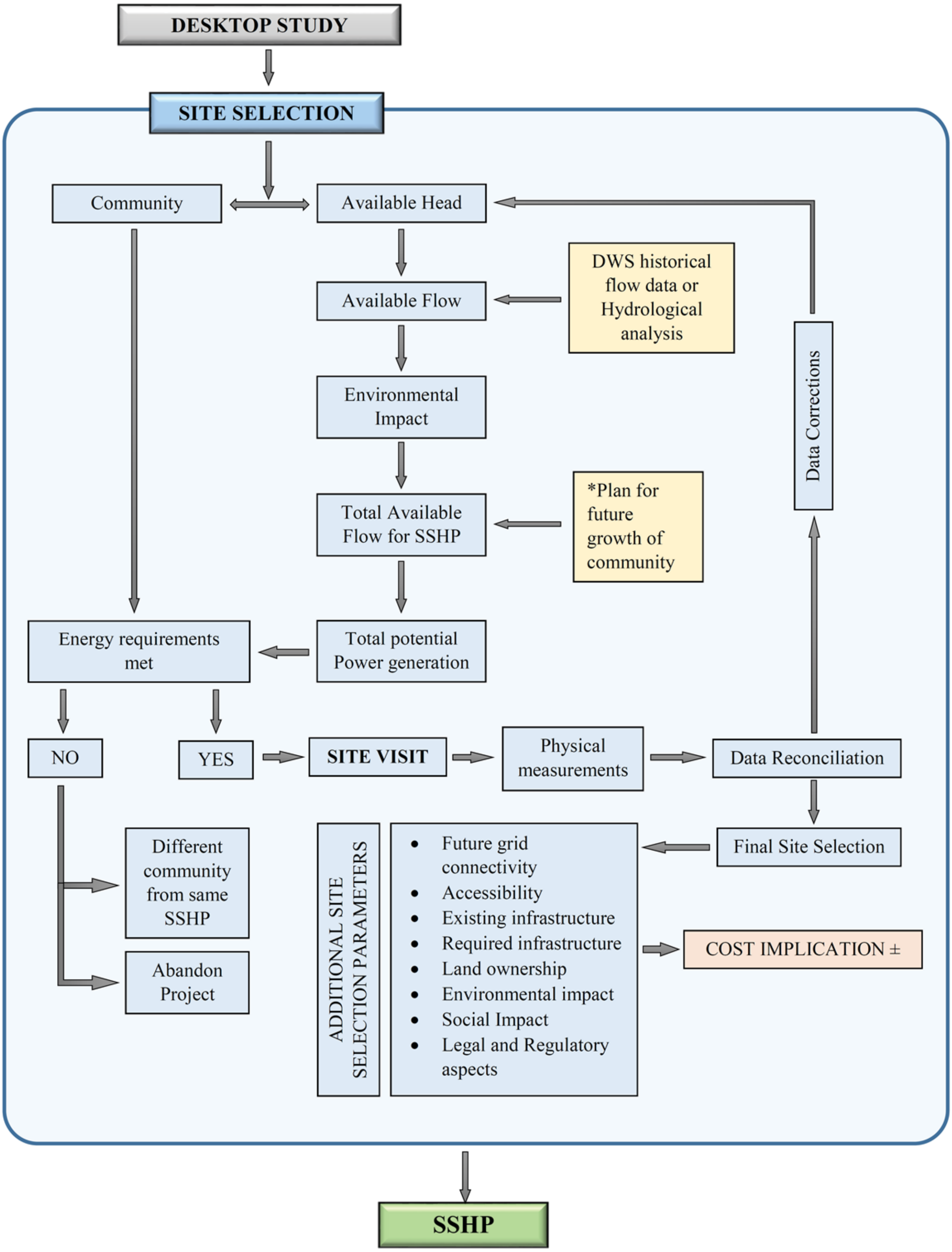

Fig. 1 Implementation Model – Site Selection

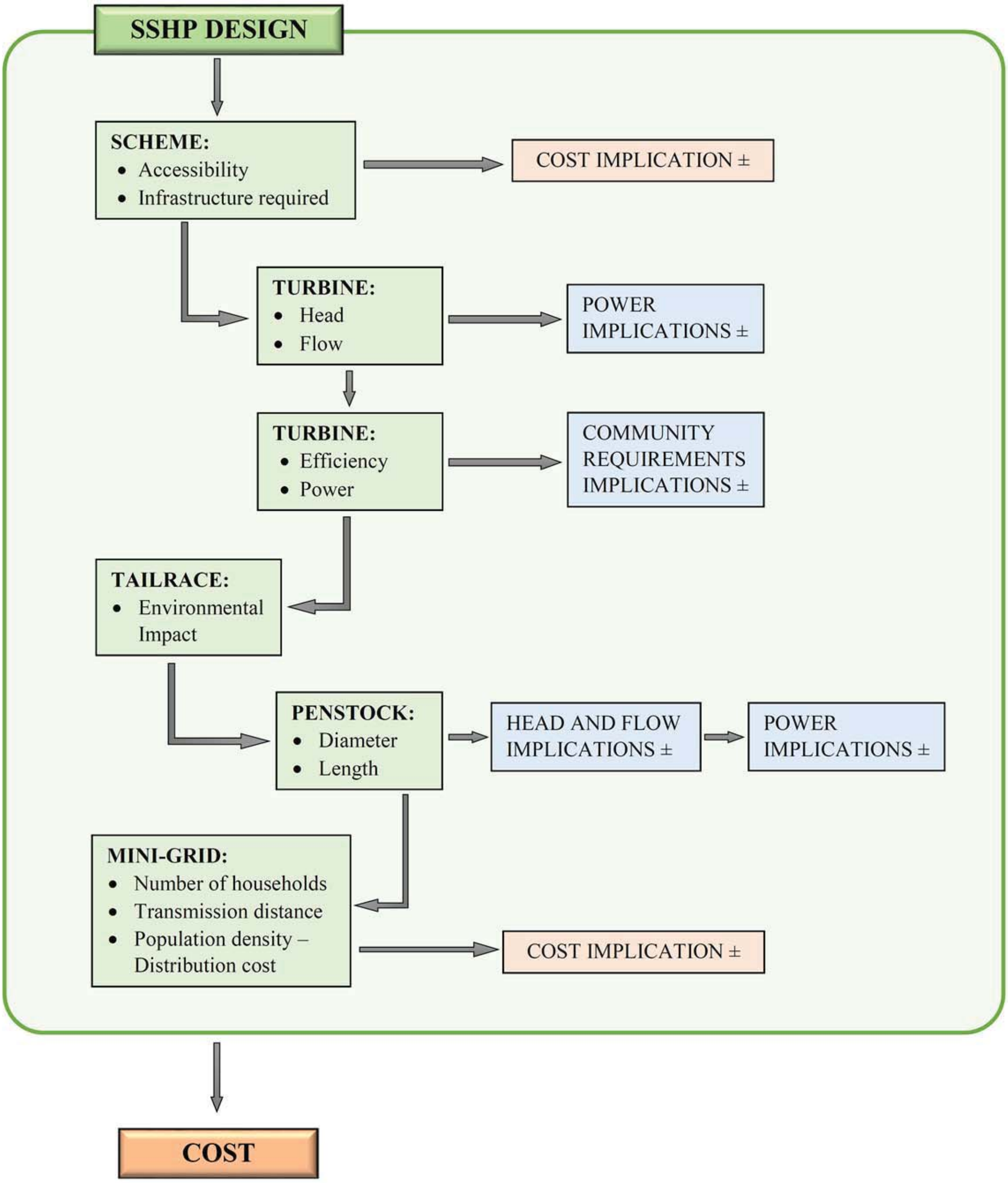

Fig. 2 Implementation Model – SSHP Design

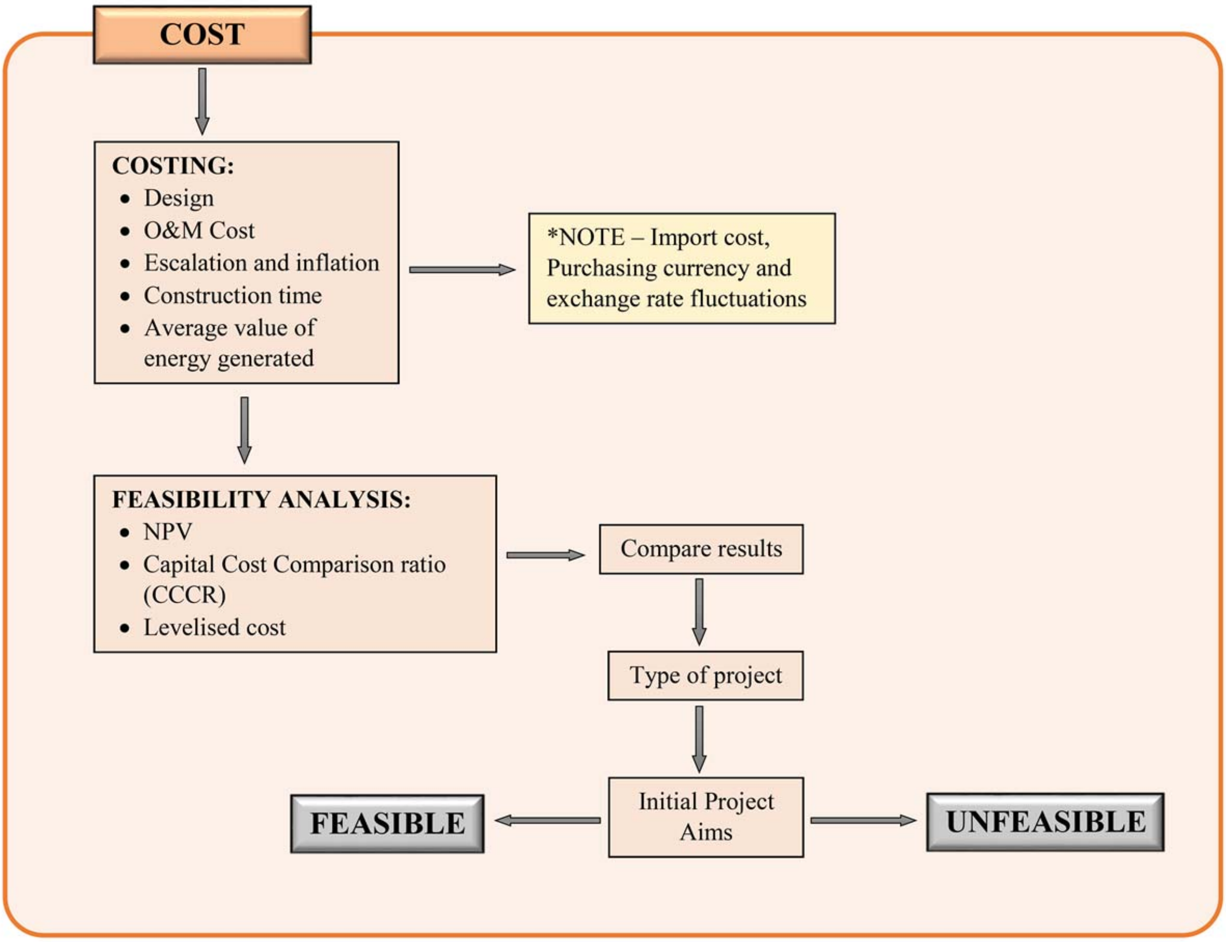

Fig. 3 Implementation Model – Costing

IV. FINANCIAL ANALYSIS

The designs for several selected sites were priced and analyzed financially. The financial analysis is linked to the description thereof in the implementation model. The designs for the different selected sites were priced using pricing models obtained from the civil construction industry from both contracting and consulting engineers. A bill of quantities was developed and compiled for each design. Parameters within the scheduled bill of quantities could be changed to suite similar sites within different technical parameters e.g. head, flow, penstock length and diameter, and transmission line lengths.

The financial analysis of the designed sites was done based on the life-cycle cost of the SSHP plant, including capital cost from the scheduled bill of quantities and the operational and maintenance cost of the plant. Annual operation and maintenance (O&M) cost of the SSHP were calculated as a percentage of the capital cost, as per industry standards, and assumed escalation factors were used to calculate the NPV of each component of the annual O&M cost. Table II shows the calculation of the O&M cost components.

The designed sites were evaluated on NPV, Internal Rate of Return (IRR), Levelised Cost of Energy, Financial Payback Period, and CCCR.

A CCCR for each installation was calculated by comparing the capital cost of the installation to the capital cost of providing electrical infrastructure (transmission and distribution lines) to connect the rural settlement or community to the existing local or national electricity grid. Therefor the cost benefit of a project can be calculated by the developed formula:

$$CCCR = \frac{Grid\ \ Extension\ Capital\ Cost}{SSHP\ Capital\ Cost} \tag{1}$$

TABLE I
KWA MADIBA TECHNICAL DATA

Description	Value
Design Flow Rate	150 ℓ/s
Design Head	48.8 m
Design Power Output	50 kW
Penstock Length	116 m
Penstock Diameter	355 mm
Energy Losses	1.2 m

The CCCR does not take into account the cost of the electricity sales from the grid or the discounted cost of electricity from the SSHP plant. The CCCR also does not take into account electricity sales from the SSHP plant but assumes that the electricity from the SSHP is supplied at a nominal cost which only covers annual operation and maintenance of the plant. The CCCR is therefore calculated as the ratio of the capital cost of the SSHP and the cost of providing electrical infrastructure (transmission and distribution lines) to connect the rural settlement or community to the existing local or national electricity grid.

TABLE II
OPERATION AND MAINTENANCE COST COMPONENTS CALCULATION

Component	Calculation
Civil works	0.25% of Civil Works Capital Costs
Transmission	0.8% of Transmission and Distribution Capital Costs
Operation	0.4% of Total Capital Costs excluding Planning and Design Costs
Insurance	0.3% of Total Capital Costs excluding Planning and Design Costs
Electrical and mechanical works	2.0% of Electro-Mechanical Equipment (Turbines, Generators and Controls) Capital Costs

TABLE III
FINANCIAL ANALYSIS ASSUMPTIONS

Description	Assumption
Escalation of Operational costs	8%
Escalation of Maintenance cost	10%
Escalation of other costs	10%
Escalation of Energy costs	10%
Discount rate (Value of Capital)	5%
Construction time	1 year
Expected operational life	40 years
Average value of generated electricity	0.59 R/kWh [a]

[a] The average value of generated electricity was calculated using the ESKOM 2013 MegaFlex tariff structure.

Due to the volatility of interest and inflation rates certain current assumptions were made for the NPV calculations. These assumptions are only accurate at any specific point in time. Formulas were developed for the calculation of the feasibility of the SSHP installations. Within these formulas the different assumptions made can be changed and a sensitivity analysis can be performed on e.g. different inflation rates or different discount rates. Table III shows the assumptions, based on current market trends and energy costs, that were made and applied to the NPV calculations.

Table IV shows the total capital cost for the development of a SSHP at the Kwa Madiba (Thina Falls) proposed site. With the calculated capital cost and the methodology discussed for the financial analysis, the site was analyzed and the following results obtained:

1) NPV = R 9 481 367
2) IRR = 9.68%
3) Levelised Cost of Energy = 102.58 c/kWh
4) Financial Payback Period = 22 – 23 years
5) CCCR = 0.38

The results of the financial analysis can be used in evaluating the feasibility of the proposed SSHP installation. The results of the financial analyses and the bill of quantities were used in developing feasibility and design charts. The development of these charts aim to simplify calculations within the pre-feasibility stage of a project in order to evaluate the viability of SSHP installation for the rural electrification.

TABLE IV
KWA MADIBA CAPITAL COST

Item	Description	Amount (ZAR)[a]	% of Cap. Cost
A	**PLANNING AND DESIGN COSTS**	**555 194**	**11%**
A.1	Prefeasibility Study	50 000	
A.2	Design	374 218	
A.3	Legal and Regulatory	74 843	
A.4	Environmental and Social Assessment	56 132	
B	**CIVIL WORKS**	**1 337 910**	**27%**
B.1	Preliminary and General Costs	190 971	
B.2	Preparation of Site	27 356	
B.3	Turbine Room	180 015	
B.4	Inlet Works	35 895	
B.5	Tailrace Works	55 962	
B.6	Pipework and valves (Supply and Install)	847 709	
C	**ELECTRO-MECHANICAL EQUIPMENT**	**2 343 804**	**48%**
C.1	Turbine	691 200	
C.2	Generator	Incl. C.1	
C.3	Control Units	Incl. C.1	
C.4	Transmission Infrastructure	1 514 364	
C.5	Import Costs	138 240	
D	**IMPLEMENTATION COST**	**684 161**	**14%**
D.1	Commissioning, erecting and project management provided by supplier	117 190	
D.2	Construction supervision	276 128	
D.3	Training	20 736	
D.4	Spare components	20 736	
D.5	Telemetry	41 472	
D.6	Contingencies	207 898	
	TOTAL:	**4 921 071**	**100%**

[a] Amounts were calculated in May 2015 - ZAR/USD exchange rate = R 11.97/$ 1.00, ZAR/Euro exchange rate = R 13.59/€ 1.00,

V. FEASIBILITY AND DESIGN CHART DEVELOPMENT

Following the feasibility study of the designed SSHP plants, a design chart was developed for future potential SSHP plant projects.

The methodology followed in conducting the feasibility analysis for future potential sites consisted out of the following steps:

Step 1: Developing cost formulae from the priced Bill of Quantities (BOQs), literature and past projects for the different components of the SSHP

Step 2: Developing income/saving formulae from SSHP literature, current and predicted energy costs and past projects.

Step 3: Developing a NPV formula, CCCR formula and levelised cost formula for SSHP projects for the different types of plant installations focused on within the scope of the study.

Step 4: Setting up a model for the development of a design chart for a SSHP.

Step 5: NPV, CCCR and levelised cost calculations with different model scenarios and variable parameters within the developed formulae.

Step 6: Design chart development from different model scenarios

Step 7: Analyzing and interpreting results

For the financial analysis and calculation of the different formulae within the scope of the study, the base year for construction was used as 2015 and the current Rand/Euro exchange rate at the time of the analysis was used as R 13.59/€ and the current Rand/USD exchange rate at the time of the analysis was used as R 11.97/$.

Formulae were developed for calculating the NPV for different configurations or schemes of SSHP. The paper focusses on the design chart development of a conventional Run-off-river Scheme incorporated for SSHP for rural electrification. To develop the formulae for the calculation of the NPV the following cost and income/saving formulae were developed:

1) Capital Cost
2) Operation and Maintenance (OM) Cost
3) Energy Savings Cost

The three formulas were developed and combined to develop a formula for the calculation of the NPV for different SSHP schemes.

A. Capital Cost

The formulae for the capital costs were developed from the priced BOQ's by varying different parameters such as penstock diameters, penstock lengths, number of turbines, transmission line lengths etc.

1) Planning and Design Cost

The Planning and Design Cost for different SSHP Schemes are similar in the sense that the base formulas stay the same with only the variables changing from scheme to scheme.

The base formula for the Planning and Design Cost was developed as follows:

1) Prefeasibility Study – Estimated as R 50 000.00
2) Design Cost– Calculated as 9% of the Civil Works Cost, the Electro-Mechanical Equipment Cost and the Implementation Cost (excluding contingencies)
3) Legal and regulatory – Calculated as 20% of the
4) Environmental and social assessment – Calculated as 15% of the Prefeasibility Study and Design Costs.

The total Planning and Design Cost for the Run-Off-River SSHP is calculated as:

$$P\;\&\;D_{Cost} = 1.35 \times 0.09\left(CW_{Cost} + EM_{Cost} + IMP_{Cost} + Con_{Cost}\right) + 50000 \tag{2}$$

where: $P\&D_{Cost}$ = Planning and Design Cost (ZAR); CW_{Cost} = Civil Works Cost (ZAR); EM_{Cost} = Electro-Mechanical Cost (ZAR); IMP_{Cost}= Implementation Cost (ZAR); Con_{Cost} = Contingencies (ZAR).

2) Civil Works Cost

From the priced BOQ's the variable for the calculation of the Civil Works cost for the Run-Off-River SSHP schemes is inlet works, the tailrace length, penstock length and penstock diameter. By standardizing the inlet works and limiting the tailrace length to 20m, the variables for the calculation of the Civil Works Costs becomes the penstock length and penstock diameter.

The priced BOQ is based on the design and therefor incorporates the prices of designed turbine units. Formula may vary for different turbine suppliers. From the priced BOQ's the following formula was developed for the Civil Works Cost (CWC) for the Run-Off-River SSHP schemes with regression analysis by using the method of least squares for six selected penstock diameters:

1) 250mm diameter:

$$CW_{Cost} = 533.04 L_{PEN(250)} + 439266 \tag{3}$$

where: CW_{Cost} = Civil Works Cost (ZAR); $L_{PEN(250)}$ = Length representative of a 250mm diameter Penstock (m).

2) 315mm diameter:

$$CW_{Cost} = 850.38 L_{PEN(315)} + 462182 \tag{4}$$

3) 355mm diameter:

$$CW_{Cost} = 1032.3 L_{PEN(355)} + 481429 \tag{5}$$

4) 400mm diameter:

$$CW_{Cost} = 1267.9 L_{PEN(400)} + 517156 \tag{6}$$

5) 450mm diameter:

$$CW_{Cost} = 1569.5 L_{PEN(450)} + 542544 \tag{7}$$

6) 500mm diameter:

$$CW_{Cost} = 1898.9 L_{PEN(500)} + 560547 \tag{8}$$

3) Electro-Mechanical Cost

From the priced BOQs for the Electro-Mechanical components of the SSHP, it was observed that the cost of the medium voltage (MV) line is related to change in the transmission line length and the cost of the low voltage (LV) line is related to a change in the distribution line length which correlates directly to the amount of households connected to the mini-grid. If the aim is to provide every household with a minimum of 1kW the amount of households which can be served is equal to the potential power generation of the SSHP in kW.

The formula developed for the Electro-Mechanical Cost for the Run-Off-River SSHP schemes is as:

$$MV_{Cost} = 293.73 \times TL + 168274 \tag{9}$$

where: MV_{Cost} = Medium Voltage line cost (ZAR); TL = Transmission line length (m). And,

$$LV_{Cost} = 17528 \times HH_{no.} + 4920 \tag{10}$$

where: LV_{COST} = Low Voltage line cost (ZAR); $HH_{no.}$ = Number of households.

Total Electro-Mechanical Cost (EM_{Cost}):

$$\begin{aligned} EM_{Cost} &= 293.73 \times TL + 168274 \\ &\quad + 17528 \times HH_{no.} + 4920 + TUR_{Cost} \end{aligned} \tag{11}$$

$$\begin{aligned} \therefore EM_{Cost} &= 293.73TL + 17528HH_{no.} \\ &\quad + TUR_{Cost} + 292244 \end{aligned} \tag{12}$$

where: EM_{Cost} = Electro-Mechanical Cost (ZAR); TL = Transmission line length (m); $HH_{no.}$ = Number of households; TUR_{Cost} = Turbine, Generator and Control System Cost + Import cost (Estimated at 20%) (ZAR).

4) Implementation Cost

The implementation cost component of the Capital Cost of the SSHP was split as follows and calculated:

1) Commissioning, erecting and project management provided by the Supplier – calculated as 5% of the Electro-Mechanical Cost:

$$Com_{Cost} = 0.05 \times EM_{Cost} \tag{13}$$

2) Construction supervision (Consultant) – calculated as 7.5% of the Electro-Mechanical Cost and Civil Works Cost:

$$Supv = 0.075\left(EM_{Cost} + CW_{Cost}\right) \tag{14}$$

3) Training – calculated as 3% of the Turbine, Generator and Control System Cost:

$$TRAIN_{Cost} = 0.03 \times TUR_{Cost} \tag{15}$$

4) Spare components to be stored on site – calculated as 3% of the Turbine, Generator and Control System Cost:

$$SPARES_{Cost} = 0.03 \times TUR_{Cost} \tag{16}$$

5) Telemetry – calculated as 6% of the Turbine, Generator and Control System Cost:

$$TELE_{Cost} = 0.06 \times TUR_{Cost} \tag{17}$$

6) Contingencies – calculated as 5% of the Civil Works Cost, Electro-Mechanical Cost and Implementation Cost:

$$\begin{aligned} Con = 0.05(&CW_{Cost} + EM_{Cost} + Com_{Cost} + \\ &SPARES_{Cost} + Supv + 0.09TUR_{Cost}) \end{aligned} \tag{18}$$

The formula for the total Implementation Cost is therefore calculated as:

$$\begin{aligned} IMP_{Cost} &= 0.129CW_{Cost} + 0.181EM_{Cost} \\ &\quad + 0.126TUR_{Cost} \end{aligned} \tag{19}$$

where: Com_{Cost} = Commissioning Cost (ZAR); EM_{Cost} = Electro-Mechanical Cost (ZAR); $Supv$ = Supervision Cost (ZAR); CW_{Cost} = Civil Works Cost (ZAR); $TRAIN_{Cost}$ = Training Cost (ZAR); TUR_{Cost} = Turbine, Generator and Control System Cost (ZAR); $SPARES_{Cost}$= Spare components to be stored on site (ZAR); $TELE_{Cost}$= Telemetry Cost (ZAR); IMP_{Cost} = Implementation Cost.

5) Total Capital Cost

The total Capital Cost for the Run-Off-River SSHP Scheme was then calculated as,

$$\begin{aligned} TotalCap_{Cost} &= P\,\&\,D_{Cost} + CW_{Cost} \\ &\quad + EM_{Cost} + IMP_{Cost} + Con \end{aligned} \tag{20}$$

where: $Total\ Cap_{Cost}$ = Total Capital Cost; $P\&D_{Cost}$ = Planning and Design Cost; CW_{Cost} = Civil Works Cost; EM_{Cost} = Electro-Mechanical Cost; IMP_{Cost} = Implementation Cost; Con = Contingencies

As the Civil Works Cost formula changes for a change in penstock diameters the total Capital Cost for the SSHP changes. As an example the formula for the total Capital Cost for the Run-Off-River SSHP with a 355 mm diameter pipeline penstock and varying transmission line length, households served, turbine cost and currency exchange rate is as:

$$\begin{aligned} TotalCapCost_{PEN(355)} &= 1356.042L_{PEN(355)} + 403.49TL \\ &\quad + 24077.99HH_{no.} \\ &\quad + 152TUR_{Cost} + 11545170 \end{aligned} \tag{21}$$

where: $Total\ CapCost_{PEN(355)}$ =Total Capital Cost for Run-Off-River SSHP with 355mm diameter penstock; $L_{PEN(355)}$ = Length of 355mm diameter Penstock; TL = Transmission line length (m); $HH_{no.}$ = Number of households; TUR_{Cost}= Turbine, Generator and Control System Cost (ZAR).

B. Operation and Maintenance Cost

The annual operation and maintenance cost of the run-off-river SSHP scheme were calculated following the methodology in Table II. Therefore, the total Annual Operation and Maintenance Cost (OM) of the individual SSHP schemes was calculated as:

$$\begin{aligned} OM_{Cost} &= 0.0025CW_{Cost} + 0.02TUR_{Cost} \\ &\quad + 0.008T\,\&\,D_{Cost} + 0.007Cap_{Cost} \end{aligned} \tag{22}$$

where: OM_{Cost} = Annual Operation and Maintenance Cost; CW_{Cost} = Civil Works Cost; EM_{Cost} = Electro-Mechanical Equipment Cost; $T\&D_{Cost}$= Transmission and Distribution Cost; Cap_{Cost} = Total Capital Cost

C. Energy Cost

The total annual energy cost for the base year (year 1) was calculated as in (22). The total annual energy cost for the base year (AEC_1) is used in the NPV calculation. For this calculation a total operational life as well as different inflation, escalation and discount rates need to be calculated or assumed. The NPV calculation is discussed in the following section.

$$AEC_1 = 8760\,P \times EC_1 \tag{23}$$

where: AEC_1 = Annual Energy Cost in year 1 (base year); P = Average Annual Generating Capacity (kW); EC_1 = Energy unit cost in year 1 (base year) (R/kWh).

D. Financial Evaluation

The calculated NPV formula for the SSHP schemes are given below. The civil works cost, and total capital costs within the NPV formulae differs as per the initial Civil Works Cost and Total Capital Cost formulae developed for the different configurations of penstock diameters. The NPV formula is as:

$$\begin{aligned} NPV &= T \times AEC_1 \sum_{i=1}^{T} \left(\frac{1+ESC_{ENERGY}}{1+DiscR} \right)^{t+1} \\ &- \left(0.025CW_{Cost} + 0.02TUR_{Cost}\right) \\ &+ \sum_{i=1}^{T} \left(\frac{1+ESC_{MAINT}}{1+DiscR} \right)^{t+1} \\ &- 0.04\left(CW_{Cost} + EM_{Cost} + IMP_{Cost}\right) \sum_{i=1}^{T} \left(\frac{1+ESC_{OPER}}{1+DiscR} \right)^{t+1} \\ &- [0.008\left(0.833EM_{Cost} - TUR_{Cost}\right) \\ &- 0.003\left(CW_{Cost} + EM_{Cost} + IMP_{Cost}\right)] \sum_{i=1}^{T} \left(\frac{1+ESC_{OTHER}}{1+DiscR} \right)^{t+1} \\ &- TotalCap_{Cost} \end{aligned} \tag{24}$$

where: NPV = Nett Present Value (ZAR); T = Useful design life (years); AEC_1 = Annual Energy Cost in year 1 (base year) (ZAR); ESC_{ENERGY} = Escalation of Energy Cost (%); $DiscR$ = Discount Rate (Value of Capital) (%); CW_{Cost} = Civil Works Cost (ZAR); TUR_{Cost} = Turbine, Generator and Control System Cost (ZAR); ESC_{MAINT} = Escalation of Maintenance Cost (%); EM_{Cost} = Electro-Mechanical Equipment Cost (ZAR); IMP_{Cost} = Implementation Cost (ZAR); ESC_{OPER} = Escalation of Operational Cost (%); ESC_{OTHER} = Escalation of Other Cost (%); $Total\ Cap_{Cost}$ = Total Capital Cost (ZAR).

E. Model

The feasibility model was developed for the Conventional run-off-river scheme. The flow was kept as a constant within the model at 200 ℓ/s. This figure was calculated as the amount of flow most commonly present for 95% of the time within the river sections under consideration, as well as the highest value of flow that can be rerouted without adversely affecting the environment at most of the investigated potential sites (sites with a more accurate flow record and a higher statistically estimated minimum flow may reroute larger amounts of flow).

With flow kept constant, the available head and penstock diameter was varied to obtain different scenarios within the feasibility model. By varying the head at a constant flow, the energy generated, P, also varies and by assuming a basic supply of 1kW per household (24kWh per day) the amount of households served is also calculated.

Table V shows the model developed for the feasibility analysis and design chart development. As discussed in the previous sections, the financial assessment for the different scenarios was done and analyzed by varying different parameters within the developed formulae.

The feasibility analysis of the SSHP can be approached in several different ways depending on the type of development out of which the development of the SSHP originates.

Firstly, if the development of the SSHP is a commercial development and profit based, the feasibility of the project will be determined solely of IRR on the investment.

Secondly, if the development of the SSHP is by a Non-Profit Organization or a government grant and revenue is only obtained to cover the initial capital cost and operation and maintenance costs, the feasibility of the project will be determined by the NPV.

Thirdly, if the development of the SSHP is for rural electrification for remote communities not connected to the local or national electricity grid, a CCCR of less than one will determine the viability of the project. For the purposes of the study the focus was on the latter two examples

TABLE V
FEASIBILITY AND DESIGN CHART DEVELOPMENT MODEL

Flow, Q	0.2 m^3/s		
Available Head, H [a]	5 m	10 m	20 m
Penstock Diameter, D	250 mm	250 mm	250 mm
	315 mm	315 mm	315 mm
	355 mm	355 mm	355 mm
	400 mm	400 mm	400 mm
	450 mm	450 mm	450 mm
	500 mm	500 mm	500 mm

[a] The same turbine is used for the 10 m and 20 m head model. For the 5 m head model, Low Head turbine technology is used.

VI. DESIGN CHARTS

A. NPV

The results from different scenarios from the model for the feasibility analysis were plotted to graphically obtain charts for the design of SSHP projects for different head and flow availabilities and varying penstock diameters and transmission line lengths.

Fig. 4 shows the design chart for selected head and flow scenarios for Run-of-River SSHP projects based on NPV. The diagonal lines for the different penstock diameters represent a zero NPV. The area underneath the diagonal lines represent a positive NPV and therefor a feasible installation, opposed to the area above the diagonal lines represent a negative NPV and therefor an unfeasible installation or project. The horizontal dotted lines on the graphs represent the total amount of households which can be served with 1 kW electricity for every specific SSHP scheme configuration. All penstock lengths below the household line can serve the amount of households indicated by the dotted line.

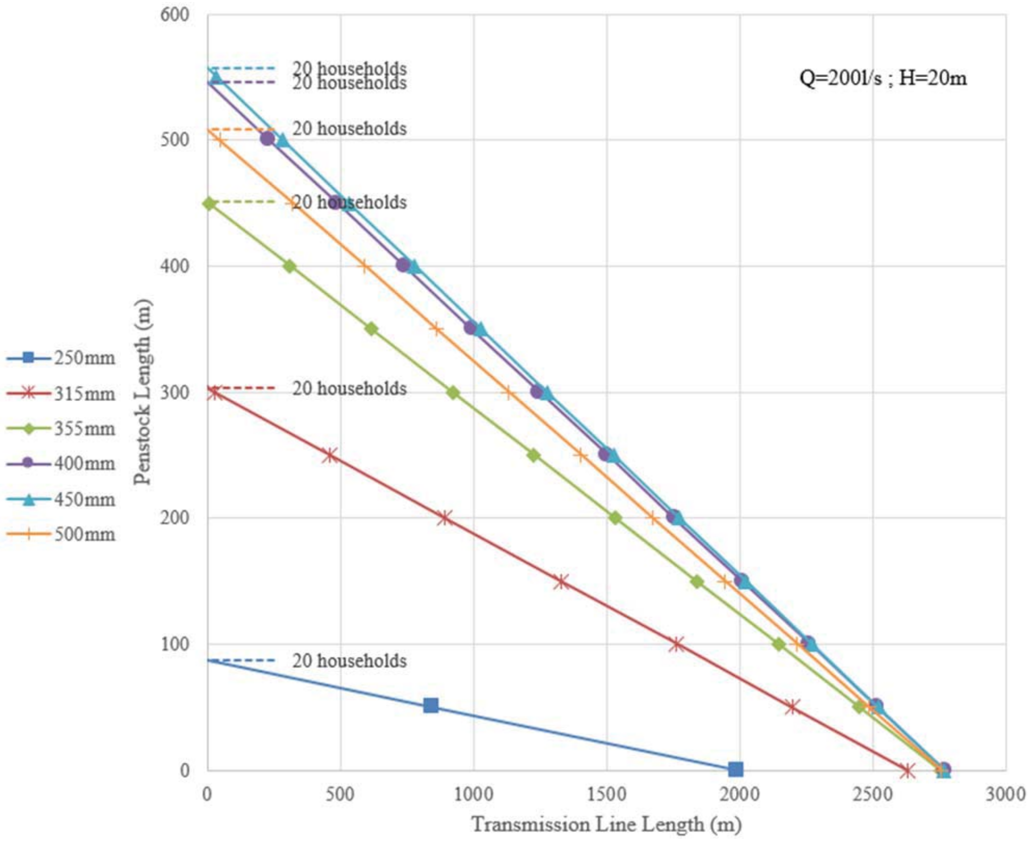

Fig. 4 Feasibility Analysis - Design Chart - Run-of-River SSHP NPV

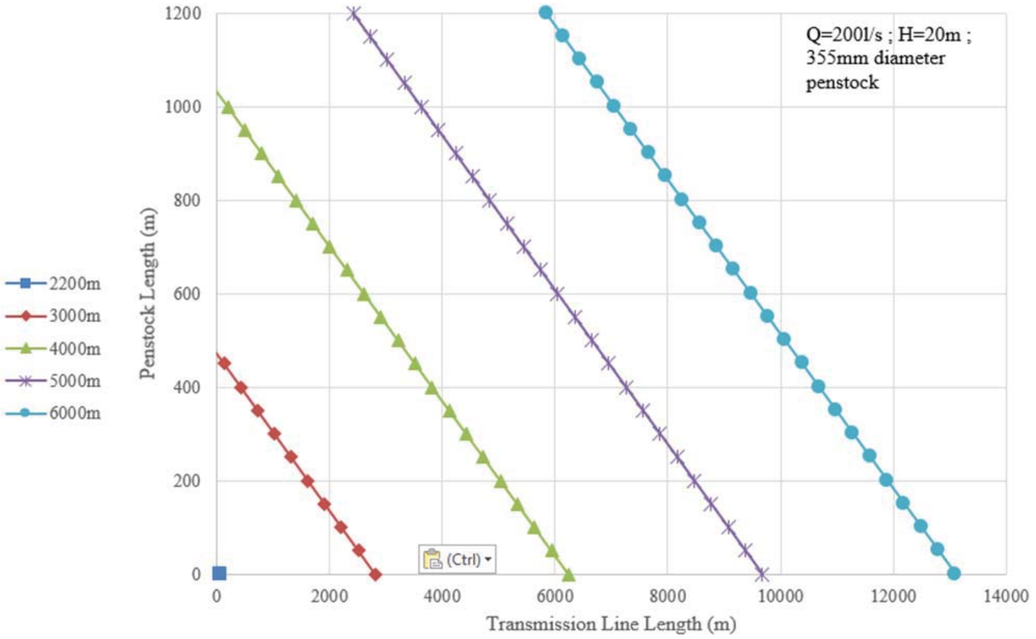

Fig. 5 Design Chart - Run-of-River SSHP CCCR

B. CCCR

The CCCR is calculated as the ratio of the capital cost of the SSHP and the cost of providing electrical infrastructure (transmission and distribution lines) to connect the rural settlement or community to the existing local or national electricity grid.

When calculating CCCR of a project the following variables are applicable:

1) Flow
2) Head

3) Penstock diameter
4) Penstock length
5) Transmission line length
6) Distance to closest existing electrical grid.

The cost of connecting the rural communities to the local or national electricity grid in Sub-Sahara Africa estimated as between ZAR 1 200 and ZAR 1 300 per meter by the World Bank [7]. This estimation compares well with similar research done by local consulting companies. Similar as the developed design charts for SSHP based on NPV, charts for CCCR of less than 1 for different penstock diameters were developed. Fig. 5 shows an example of such a chart for a 355 mm diameter penstock for a Run-Off-River SSHP (Q=200 ℓ/s; H=20 m), with the diagonal lines representing a CCCR of 1.00. Everything below the line is a CCCR of less than 1.00 and therefor feasible and everything above the line is a CCCR of more than 1.00 and therefor unfeasible. The different diagonal lines were constructed using different lengths to the existing electricity grid as can be seen in the legend. Following a similar approach can be used to develop charts for CCCR of different configurations and SSHP projects.

VII. CONCLUSIONS AND RECOMMENDATIONS

From the feasibility analysis of the SSHP projects based on the NPV and CCR of the project as well as the levelised cost of energy generated by the SSHP, as well as the design chart development, the following conclusions were made.

1) For shorter lengths of transmission lines, the SSHP is feasible based on NPV.
2) Long lengths of transmission line make SSHP unfeasible based on NPV.
3) Some technical possible SSHP projects have negative NPV based on long transmission line lengths or low income from power generated, but are still an option for rural electrification based on a low CCCR.
4) Turbine cost and distribution line cost are the major influences on the cost and feasibility of SSHP.
5) High head, short transmission line and islanded mini-grid SSHP installations are the most feasible.
6) Levelised cost of SSHP is high for low power generation.
7) Levelised cost for extending the existing grid is much high than SSHP at low power generation than at higher power generations, which makes SSHP feasible for low power generation.
8) CCCR for SSHP with high levelised cost still indicate feasibility of SSHP for rural electrification.

Recommendations for further research that emanated from the study is as follows:

1) Development of more efficient low head turbine technologies for electricity generation for rural electrification within the South African river setting.
2) Further feasibility studies and design chart developments incorporating more turbine technologies and configurations.
3) SSHP development from existing water distribution system for rural settlements within urban areas.
4) Development of a payment structure model for rural electrification

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