SELECTING THE OPTIMUM HYDROPOWER SCHEME CAPACITY

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ABSTRACT

To select the optimum dam height and plant capacity, a high-level design should be prepared for a range of the dam heights and plant sizes at a potential site. The capital and operating costs should be determined for the proposed scheme for the expected life of the project. Then the long-term energy production should be calculated using a hydrological model. The marginal cost and the marginal revenue should be calculated for the range of scheme sizes. The optimum scheme size is when the marginal cost exceeds the marginal revenue. A sensitivity analyses should be done on all the main input parameters. This paper deals with selecting the optimum scheme capacity for a site using the established economic optimisation method of total revenue – total cost approach and marginal analysis, which mitigates the bias in selecting the scheme capacity.

1. BACKGROUND

Hydropower electricity generation in the world has reached a new high of approximately 4200 terawatt hours (TWh) in 2018, of this 4200TWh, only 138 TWh, 3.3 %, is contributed from Africa. New hydropower capacity of 21.8 Gigawatts (GW) was put into operation in 2018, in which Africa contributed 1 GW from 7 different countries. (IHA, 2019). This bringing Africa's total installed capacity to 36.3GW, 2.8 % of the world's total installed capacity. Figure 1 shows the 2918 distribution of hydropower development across the different regions of the world.

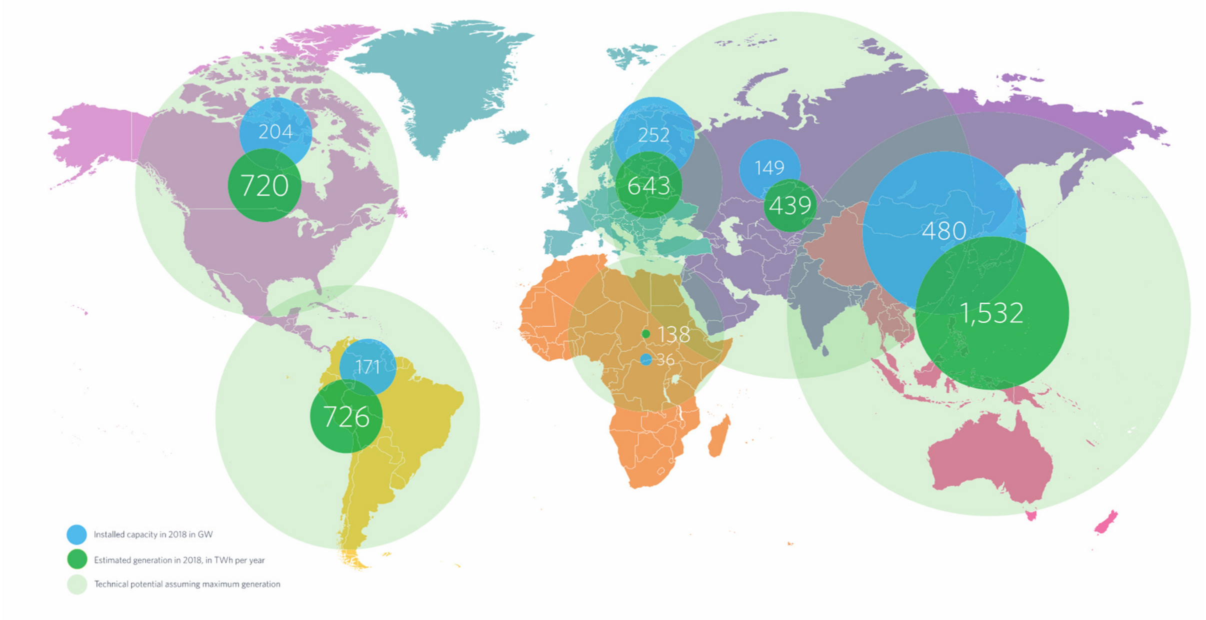
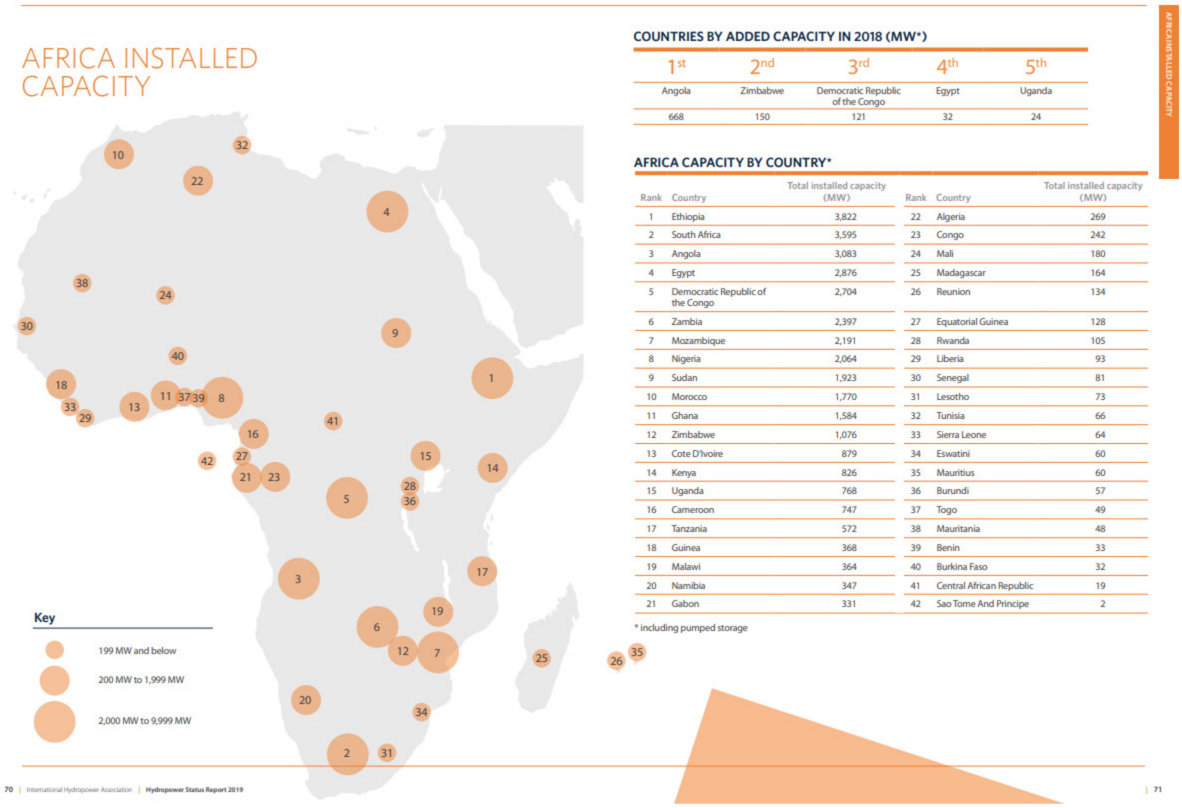


Figure 1: Hydropower Capacity and Generation by Region (IHA, 2019)

With 640 million Africans having no access to electricity according to the African Development Bank Group (ADBG)(African Development Bank Group, 2019) there is a great need for energy generation in Africa. Many sources state that Africa has the largest percentage of untapped hydropower potential with only 11 % utilised. Figure 2 shows the distribution of hydropower development across the Africa.

It should be noted that a large proportion of the installed hydropower capacity in South Africa is pumped storage to balance the daily power fluctuation in the South Africa grid.



COUNTRIES BY ADDED CAPACITY IN 2018 (MW*)

1st	2nd	3rd	4th	5th
Angola	Zimbabwe	Democratic Republic of the Congo	Egypt	Uganda
668	150	121	32	24

AFRICA CAPACITY BY COUNTRY*

Rank	Country	Total installed capacity (MW)	Rank	Country	Total installed capacity (MW)
1	Ethiopia	3,822	22	Algeria	269
2	South Africa	3,595	23	Congo	242
3	Angola	3,083	24	Mali	180
4	Egypt	2,876	25	Madagascar	164
5	Democratic Republic of the Congo	2,704	26	Reunion	134
6	Zambia	2,397	27	Equatorial Guinea	128
7	Mozambique	2,191	28	Rwanda	105
8	Nigeria	2,064	29	Liberia	93
9	Sudan	1,923	30	Senegal	81
10	Morocco	1,770	31	Lesotho	73
11	Ghana	1,584	32	Tunisia	66
12	Zimbabwe	1,076	33	Sierra Leone	64
13	Cote D'Ivoire	879	34	Eswatini	60
14	Kenya	826	35	Mauritius	60
15	Uganda	768	36	Burundi	57
16	Cameroon	747	37	Togo	49
17	Tanzania	572	38	Mauritania	48
18	Guinea	368	39	Benin	33
19	Malawi	364	40	Burkina Faso	32
20	Namibia	347	41	Central African Republic	19
21	Gabon	331	42	Sao Tome And Principe	2

* including pumped storage

Figure 2: Africa Installed Capacity (2019 Hydropower Status Report, IHA, 2019)

With Africa having the largest percent of untapped hydropower potential, hydropower projects are an important driver for new dam construction projects in Africa. With there being a shortage of public finance for power development in Africa there is a huge emphasis on needing to attract private sector financing, this comes with a certain difficulty in which one must mitigate the risks that are perceived by the investors. It is important for developers to optimise their investments and the African challenges that one must contend with deter private capital (Kalitsi EAK, 2003). Thus, it is important to optimize the capacity of new hydropower schemes when such opportunity comes.

In selecting the optimum capacity for a new hydropower plant, it is important to consider a range of dam heights and plant sizes for a site. The annual average energy production for a site is dependent on both factors as well as other factors such as the water resource available and electricity tariff structures. This paper will outline the method used to select the optimal hydropower scheme capacity for a potential site. A theoretical case study is presented to demonstrate this method.

2. INITIAL SCHEME LAYOUT

For any new (greenfield) hydropower scheme or expansion of an existing scheme, there are usually an infinite number of possibilities for the scheme layout. While considering the project scope requirements and assessing the constraints of topography, hydrology, geology, the environment, connection to grid, existing infrastructure and funding availability the designer must make certain decisions in the beginning to reduce the number of alternatives.

Experience of the designer influences the selection of possible scheme layouts. Many of these early decisions are usually reliant on heuristics, which are subject to bias. However, any new scheme requires some point of departure for a solution. Initial conceptual scheme layouts must be defined so they can be investigated. In order to mitigate the bias in selecting the scheme capacity, established economic optimisation method of marginal analysis is used. There are other techniques which further reduce the bias in scheme layout selection but are not subject of this paper.

The initial civil conceptual scheme layout will usually consist of high-level design options of the most crucial infrastructure such as the sizes and types of dam, intake configuration, conveyance systems, powerhouse, mechanical equipment and transmission. These structures will be sized and sited for the various capacities that the designer must define within the constraints of the site.

3. BACKGROUND OF ECONOMIC THEORY USED FOR OPTIMISING SCHEME CAPACITY

Once the conceptual scheme layout is configured, the process to select the scheme capacity should be based on economic analyses with an objective to maximise profit. Should the conceptual scheme layout not be obvious from the initial design then the process of optimisation may be required for several different scheme layouts.

3.1 Total Revenue-Total Cost Approach

To identify the ideal capacity for maximum profits, this is where the production and selling of a quantity of energy where total revenue (TR) is at its greatest vertical distance above total cost (TC) as shown in Figure 3. In this case TR being the total amount of energy sales bought back to a net present revenue value (NPR) and TC being a sum of the total fix costs and variable costs bought back to a net present cost (NPC) value. Any scheme capacity where TR is above TC a profit can be made, where the TR and TC curves intersect this is the break-even point, and beyond those points where the TC curve is above the TR curve, losses will be observed.

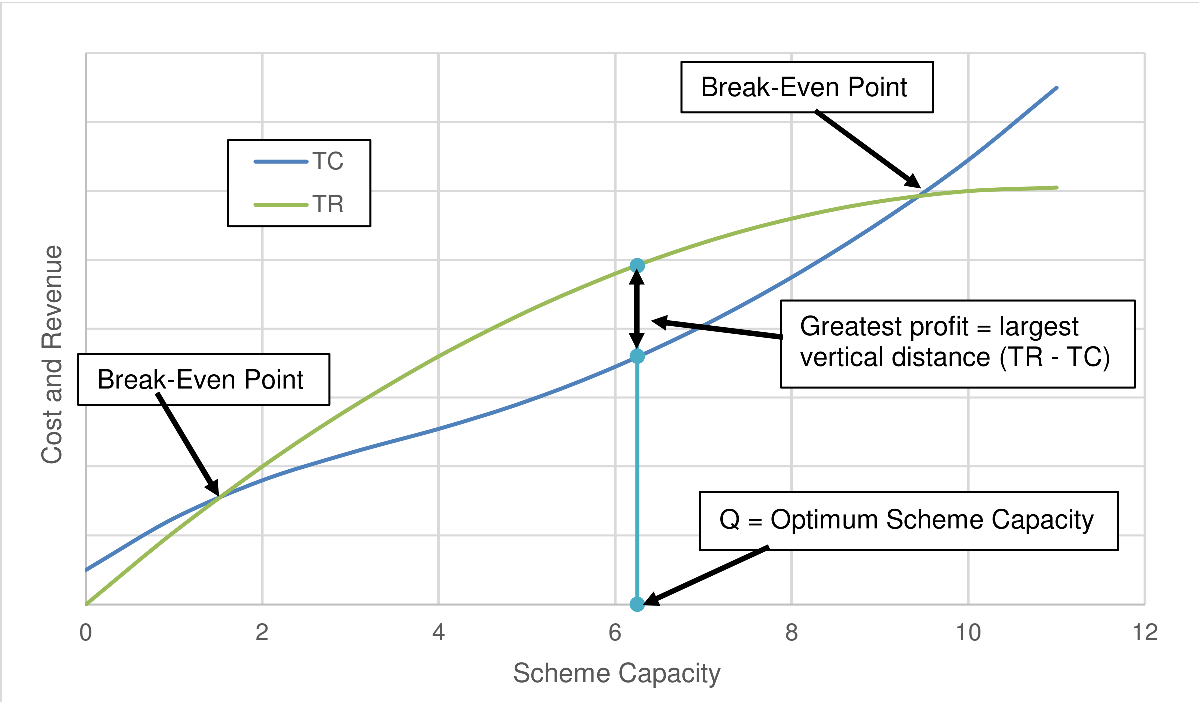


Figure 3:Total Revenue- Total Cost Versus Scheme Capacity

In Figure 3, profit is maximised at scheme Capacity Q, where the difference between TR and TC is at its largest value. It is difficult to distinguish exactly where the maximised profit scheme capacity value is by looking at the plotted total cost and revenue versus scheme capacity graph, hence the marginal analysis should be done in conjunction.

3.2 Marginal Analysis

Marginal analysis is used to analyse the additional revenue and additional cost that is incurred when there is the addition of a unit, in this case capacity, to the system. This is a tool used to maximise potential profits. Marginal Analysis utilises the marginal revenue (MR) and marginal cost (MC) of the scheme to determine the optimum scheme capacity. MC is the additional incremental cost of increasing the scheme capacity by an incremental step and MR is the additional incremental revenue resulting from the incremental increase in scheme capacity. The optimum scheme capacity occurs when the MC equals the MR, when MC is lower than MR, the capacity should be increased to reach the optimum scheme capacity, but if it is not a profit is still made for each unit that is produced, but when MR is lower than MC then the optimum capacity has been exceeded and should be decreased. This is presented in Figure 4 below.

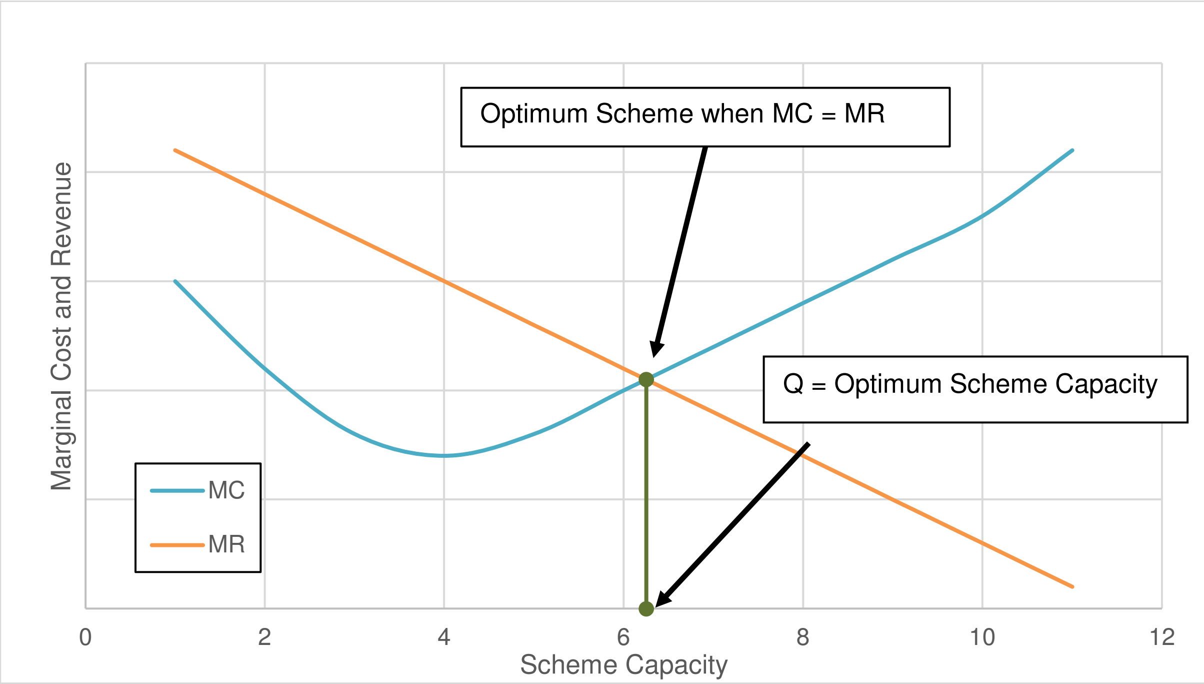


Figure 4: Marginal Analysis

The optimum scheme capacity Q shown in Figure 3 & 4 corelate for both profit methods and is presented below in Figure 5.

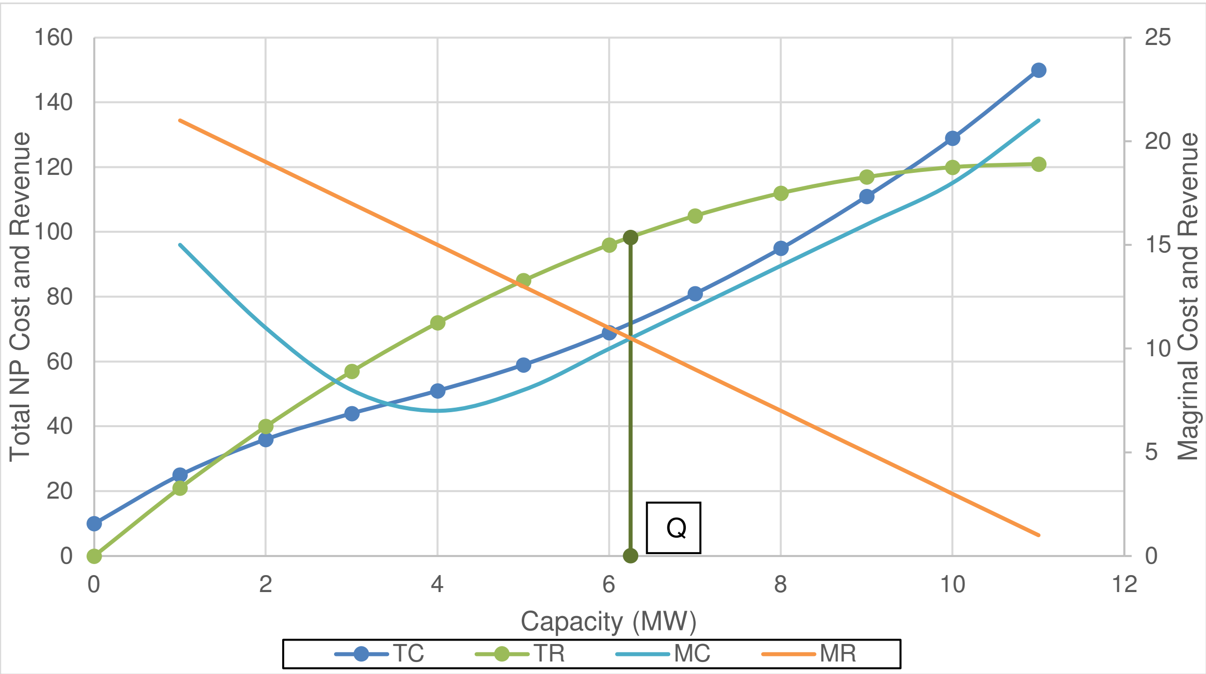


Figure 5: Total Revenue - Total Cost and Marginal Analysis Versus Scheme Capacity

Average revenue (AR) and average total cost (ATC) can be calculated and plotted, this indicates the type of profit that can be expected from the scheme. Seen in

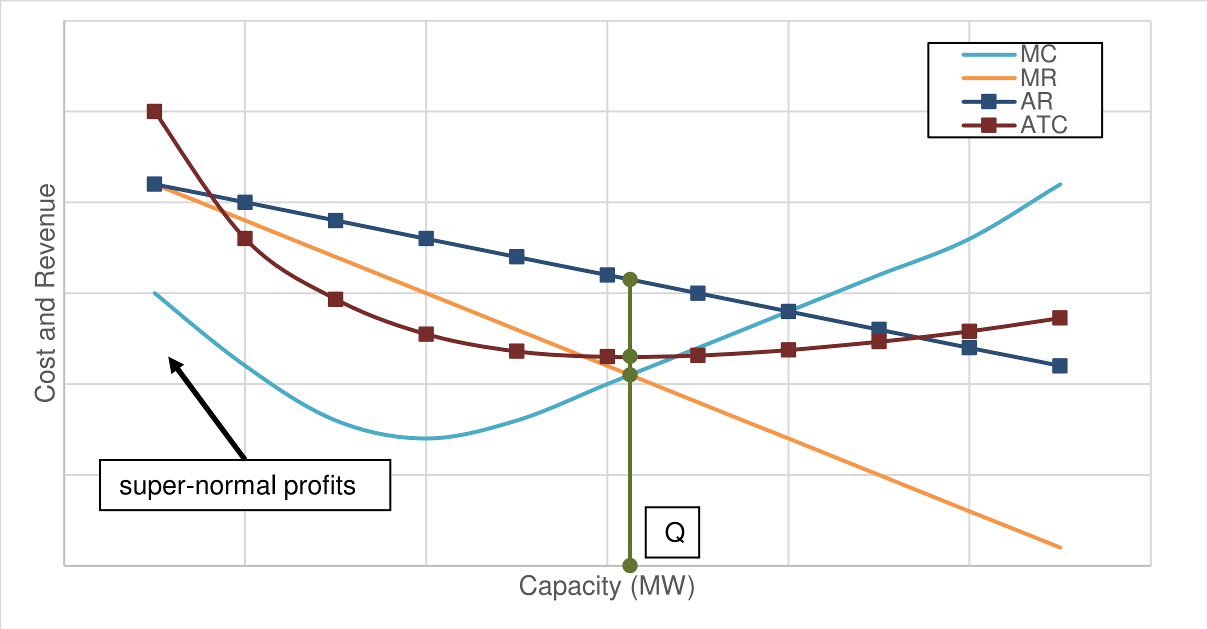


Figure 6, the blue rectangle formed using the interception points of the AR and ATC line with the Q line taken back to the y axis, indicates an area where super-normal profits can be expected, where super-normal profits are profits that are higher than breakeven. Normal profit, also known as breakeven point, is achieved when AR is equal to ATC at capacity Q, the two curves only touch at a point and then taper off in different directions. Losses occur where the AR curve is below the ATC curve at the intersection point of Q.

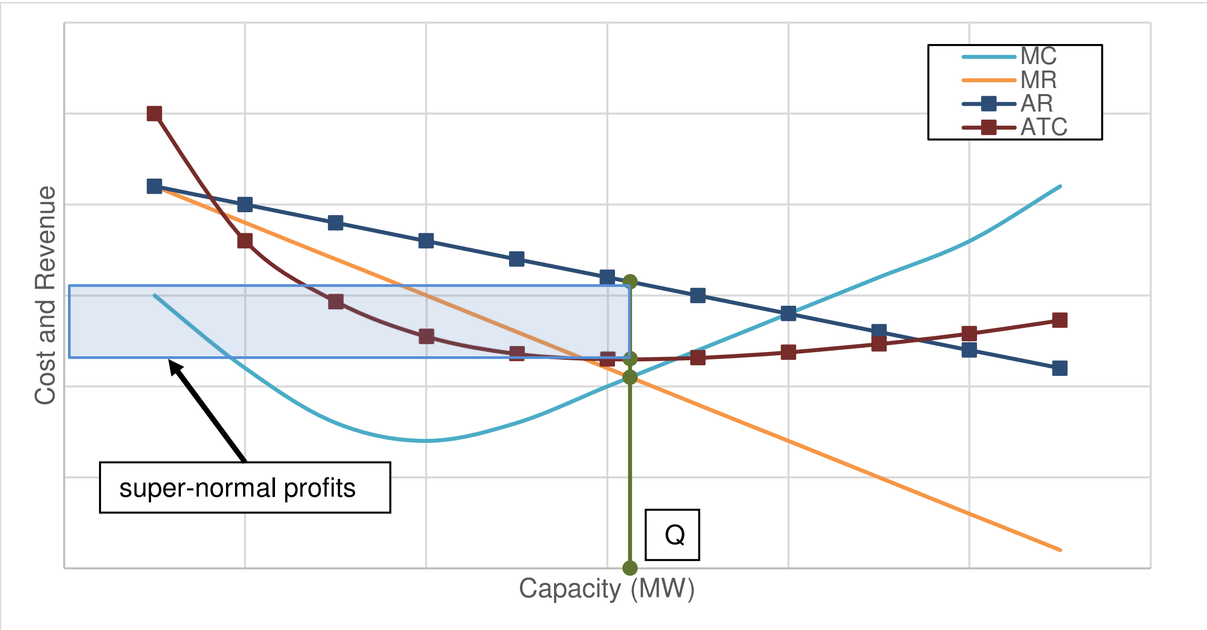


Figure 6: Average Revenue and Average Cost

Total revenue- total cost and marginal analysis are significant in economic theory as it is assumed a profit maximising firm will produce up to the capacity where marginal cost (MC) equals marginal revenue (MR). Performing marginal analysis on the costs and revenue reveals the optimum scheme capacity for a maximum return on investment. Therefore, once a conceptual scheme layout has been determined, it is important to scale up and down the scheme capacity and determine the marginal increase in revenue and cost for the range of scheme capacities.

Marginal revenue generally diminishes for a hydropower scheme because of the hydrological limits., Therefore at a certain scheme capacity the marginal costs will always become higher than the marginal revenue, because of diminishing returns from the scheme. This decrease in marginal revenue is referred to as the 'law of diminishing marginal returns'.

It should be noted that the point of maximum return of investment is at the scheme capacity where the marginal cost equals marginal return and is not necessarily the same as the lowest levelized cost of energy (LCOE). The scheme capacity where the marginalised cost of energy equals the marginal return is however equal to the maximum NPV and IRR from the scheme. If time of use (TOU) tariffs are being used, it is very important not to use the LCOE to determine the optimum scheme capacity and rather marginal analysis.

4. CASE STUDY: SELECTING THE OPTIMUM HYDRO POWER SCHEME SIZE

4.1 Conceptual scheme layout

A proposed scheme being studied to feasibility level was selected for a marginal analysis to determine the optimum scheme capacity. It is in the Southern African region and subject to South African Power Pool (SAPP) tariffs.

Downstream of a large existing dam which makes large releases for irrigation, the river downstream has a steep gradient. There is an existing PowerStation at the dam which generates peak power from the irrigation releases. The river invert level some distance downstream is approximately 80m lower. Combined with the releases from the upstream Dam and the steep river gradient, this provides a good opportunity to build a new small hydropower scheme.

The proposed hydropower scheme will be a new scheme and the envisaged scheme comprises the following key components:

- A new intake structure at the diversion weir, fitted with screens, bulkhead gate, control gate, stilling basin and a reject weir leading to the concrete lined power canal;
- The total power canal system will be concrete lined.
- Intersection of two existing valleys along the canal route results in the need for two siphons.
- An integrated reinforced concrete forebay and penstock intake with screened intake;
- A single high-pressure penstock, supported on plinths, that bifurcates near the powerhouse position to serve two generation units (Francis);
- A surface powerhouse located at the end of the penstocks. The powerhouse is envisaged to comprise a reinforced concrete substructure, equipped with twin Francis turbine and generating sets, and associated equipment. A steel superstructure will house the loading bay for the turbines and generator sets. A travelling crane will be positioned over the turbine hall for the installation and removal of the turbines, generators and main inlet valves.
- A tailrace structure,
- A downstream concrete dam wall to form a re-regulating pond to balance the river releases.
- A 66 kV step up transformer at a substation and transmission line to the nearest interconnection point.

A range of scheme capacities were analysed for the proposed scheme layout described above.

4.2 Cost Estimates

Drawings were prepared on the scheme layout to measure the quantities. A cost model was constructed for the scheme making it efficient to determine the cost variation with changing scheme capacity. Cost estimates were determined by measuring the main quantities for the scheme and applying current rates. Also added to the costs were preliminary and general, contingencies, miscellaneous for unmeasured items, engineering services and VAT. Cost estimates were developed for civil works, mechanical & electrical equipment and transmission for each capacity. Total capital costs, capital cost per MW were calculated for the range of sizes.

Based on the above information a model was built to calculate the Net Present Cost (NPC), Net Present Revenue (NPR) present value per megawatt hour (Mwh) and the LCOE of each option using the following parameters, capital cost, construction period, years of operation, annual O&M cost and the discount rate.

4.3 Revenue Estimates

Revenue estimates were made using a hydrology model to determine the water availability and the resulting energy potential. The scheme will be used to offset power purchased from Eskom, therefore the Eskom TOU periods, seen in Figure 7, and tariffs, presented Figure 8, are applied. The revenue was calculated based on the time of operation and the equivalent tariff. A model was built to calculate the Net Present Revenue (NPR) of each option using the following parameters, average energy production, tariffs, years of operation, plant availability and the discount rate.

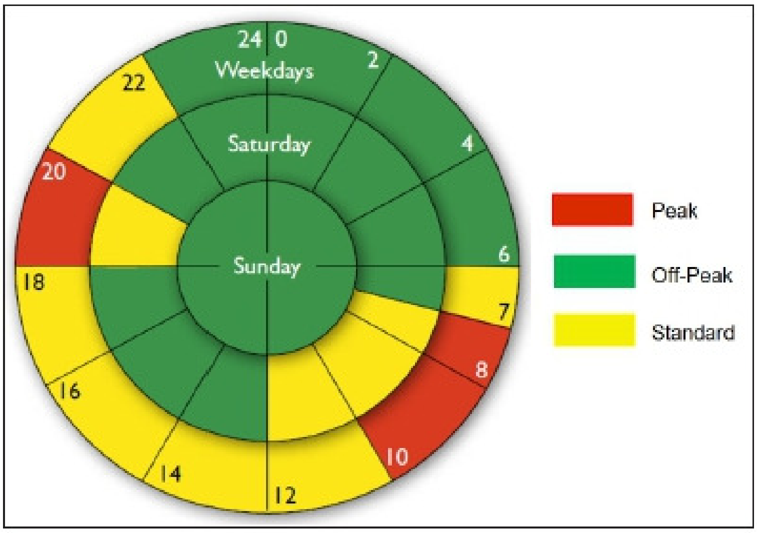


Figure 7: Eskom's defined time of use (TOU) periods (Eskom, 2019)

Table 1: Time of Use Tariffs 2019

Power Type	Rate for High Demand Months (R/kWh)	Rate for Low Demand Months (R/kWh)
Peak	R3.123	R1.105
Standard	R1.034	R0.800
Off-peak	R0.620	R0.554

*These tariffs are adjusted to include certain fixed charges

4.4 Economic Analysis

4.4.1 Total Revenue – Total Cost Approach

The calculated total net present revenue (NPR), and the net present cost (NPC), also referred to as the total revenue and total cost respectively in previous sections, for the scheme are plotted against scheme capacity in Figure 8. It can be observed in Figure 8 that, NPR is higher than NPC, thus for all the capacity options that were analysed, a profit will be made. The NPR and NPC curves are converging at the top right and bottom left. The convergence cross over point was not reached with the options that were analysed. However, at a specific scheme capacity, the NPC will become higher than the NPR, where the scheme will make a loss.

It is difficult to see where the optimum scheme capacity for maximum profit is, by looking at the graph. Thus, the marginal analysis was modelled.

Figure 8: Total Cost and Total Revenue Versus Scheme Capacity for Case Study

4.4.2 Marginal Analysis Approach

Marginal analysis requires the calculation of the marginal revenue, which is dividing the change in NPR by the consecutive change in scheme capacity for each incremental increase in the scheme capacity, and the marginal cost, which is calculated in the same way but using the NPC. It is easier to identify the optimum scheme capacity for profit maximisation as it is at the intersection of MR and MC as seen in Figure 9. Where MR is greater than MC, indicates that profits are increasing and where MR is less than MC the profits are decreasing.

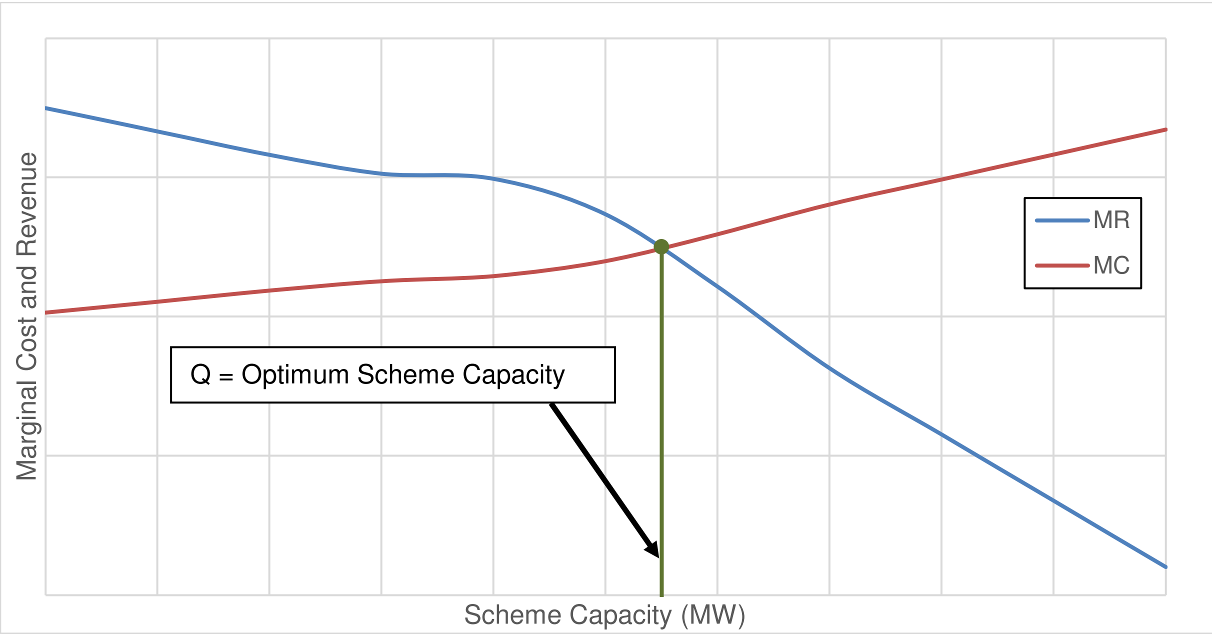
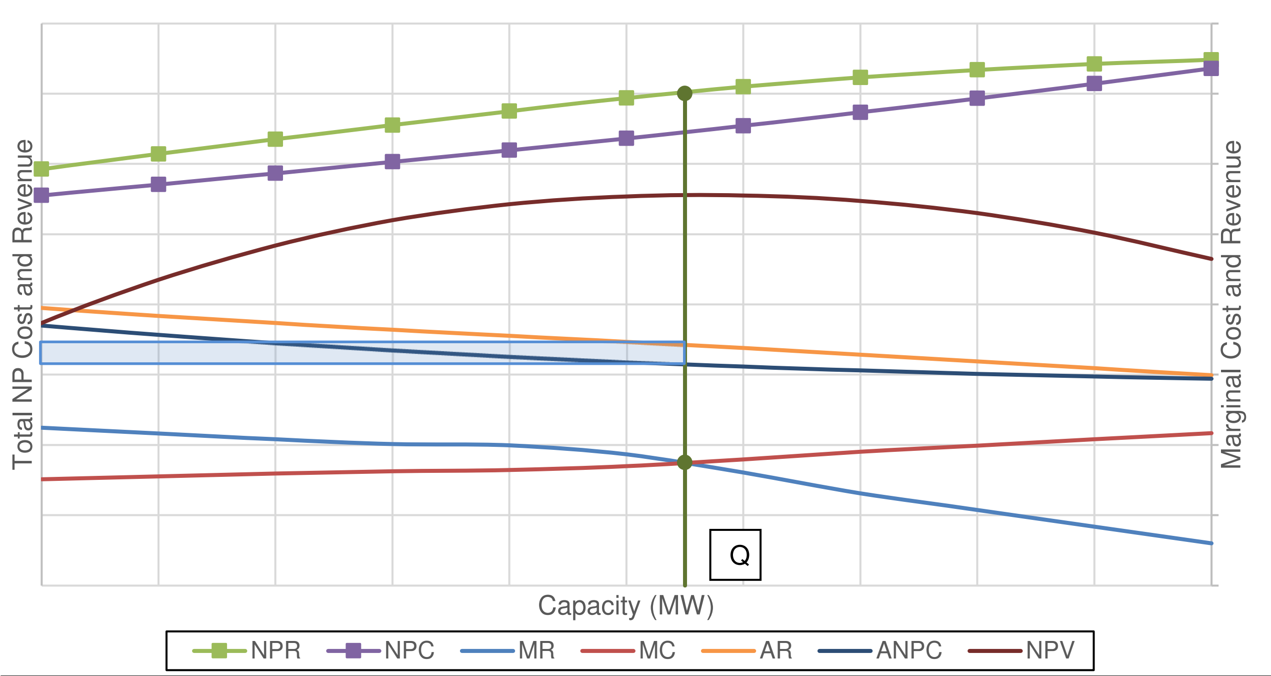


Figure 9: Marginal Analysis for Case Study

The optimum scheme capacity identified can be used to identify the maximum NPV as seen in Figure 10. It can be observed that the optimum scheme capacity identified in the total revenue-total cost and marginal analysis intersects at the peak of the net present value (NPV) curve thus correlating the two analyses. The NPV is the difference of the NPR and NPC. It can also be observed that the AR curve is above the average net present cost (ANPC), same as average cost, at Q, thus indicating super-normal profit.



*For visual purposes NPV uses the Marginal Cost and Revenue rather than the Total NP Cost and Revenue Y axis.

Figure 10: Combined Graph of Figure 8 and Figure 9 with Average Revenue and Average Costs

4.4.3 Levelised Cost of Energy

The LCOE is calculated using the NPV of the construction and O&M costs, divided by the present value of the energy generated over the life of the scheme and the results are presented in Table 2. This method is often used to determine the optimum scheme capacity. It is observed that the LCOE increases as the MW increases and it does not reflect the most economical solution as the increased plant capacity allows a greater proportion of higher value peak energy production thus it is not a good method to optimise the scheme in this study.

Table 2: Levelised Cost of Energy for Case Study

Total Power	LCOE
MW	(R/kWH)
15.00	2.066
16.00	2.083
17.00	2.103
18.00	2.124
19.00	2.149
20.00	2.175
21.00	2.202
22.00	2.229
23.00	2.256
24.00	2.284
25.00	2.313

5. CONCLUSION

NPV should be determined for a range of capacities for hydropower schemes for any new scheme, using total revenue-total cost and marginal analysis to determine the optimum capacity. The case study demonstrates how the total revenue-total cost and marginal analysis was used to determine the optimum scheme capacity in a region where Eskom TOU tariffs are applicable. It also demonstrates that it is not reliable to use lowest LCOE to determine the optimum scheme capacity where TOU tariffs are applicable and where peak power generation is the main focus.

6. REFERENCES

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