THE ECONOMIC COMPARISON OF RESERVOIR TYPE AND RUN OF THE RIVER TYPE HYDROPOWER PLANTS: A CASE STUDY FOR UPPER KOTMALE

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Department of Electrical Engineering

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Abstract

At present, greenhouse gas emissions are considered as a factor even for hydropower because of the identified gas emission possibilities. Thus when planning a large hydropower project at a selected location, it is important to take the decision on which type of power plant to construct (such as a reservoir type or run of the river type) based on an economic comparison including environmental considerations.

Out of the implemented two large run of the river type hydropower projects in Sri Lanka, Upper Kotmale was selected as the case study for this research. The existing Talawakele run of the river project and an earlier suggested Caledonia reservoir project were selected for the comparison as competitive projects.

Net greenhouse gas emissions from the both projects were estimated in this study. For the economic comparison, the levelized cost of electricity of both projects were calculated considering related costs, benefits under Clean Development Mechanism, and annual electricity generation. The results show that the unit cost of electricity generation from run of the river type project is substantially lower than that of reservoir type project. As Upper Kotmale is a peak serving plant in Sri Lanka, a separate comparison between the two projects was done considering their night peak operation. The results show a loss to the country by energy reduction due to not using the potential for reservoir type.

Based on the results of the case study, it is concluded that for future large hydropower developments, a detailed study, including Clean Development Mechanism benefits, to be carried out case by case before taking the decision on reservoir construction. The research outcome will not only be important to any remaining hydropower potential development in Sri Lanka but also to other hydropower dominant countries in the world.

Dedication

I dedicate my MSc research dissertation to my parents and all the lecturers of Department of Electrical Engineering, University of Moratuwa.

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I would first like to acknowledge my supervisors, Eng. W.D.A.S. Wijayapala, Prof. J.R. Lucas and Eng. W.J.L.S. Fernando for their guidance provided from the beginning to the end of this research regarding both technical and non-technical aspects of it. At the same time I would like to acknowledge all the staff members of Department of Electrical Engineering, University of Moratuwa for giving valuable comments during the progress review presentations.

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List of Abbreviations

Abbreviation	Description
CBSL	Central Bank of Sri Lanka
CDM	Clean Development Mechanism
CGD	Concrete Gravity Dam
E/S	Engineering Services
ECRD	Earth-Core Rockfill Dam
EIA	Environmental Impact Assessment
F/S	Feasibility Study
GEF	Grid Emission Factor
GHG	Greenhouse Gas
GOSL	Government of Sri Lanka
GPP	Gross Primary Production
JICA	Japan International Cooperation Agency
JPY	Japanese Yen
KP	Kyoto Protocol
KPS	Kelanitissa Power Station
LCIA	Lice Cycle Impact Assessment
LCOE	Levelized Cost of Electricity
LKR	Sri Lankan Rupees
NPP	Net Primary Production
NPV	Net Present Value
O&M	Operation & Maintenance
ROR	Run of the River
UKHP	Upper Kotmale Hydropower Project

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1. INTRODUCTION

1.1. Background

Energy sources used for electricity generation are categorized as conventional and non-conventional energy sources. Although renewable energy sources are usually listed under the non-conventional category, hydropower is listed under both categories. The reservoir type and large hydropower plants are categorized as conventional energy sources, while the small Run of the River (ROR) type hydropower plants are categorized as non-conventional energy sources. Small hydropower plants (<10MW) are usually developed as ROR type but large hydropower plants (>10MW) can be either reservoir type or ROR type.

When planning a large hydropower project at a selected location, it is important to take the decision whether to construct a reservoir type or ROR type based on an economic comparison including environmental and other considerations. The reason is, there are environmental, social and economic impacts of hydropower projects which cannot be neglected, especially for large hydro.

At present, greenhouse gas (GHG) emissions are considered as a factor even for hydropower because of the identified GHG (CO_2 and CH_4) emission possibilities. Disturbance to the ecosystem or loss of ecosystem is also a negative impact to the environment due to hydropower projects. This includes deforestation, damage to fish as a consequence of flow reduction and effects on waterfalls aesthetic. The latter may cause some reduction in tourism volumes. Resettlement of population is a critical social impact caused by large hydropower projects. The economic advantage of reservoir type is the ability to store water and hence to be dispatched during both wet and dry seasons. Dry seasons affect the river flow of ROR type and hence the electricity generation.

The objectives of this research are, to estimate the quantifiable advantages and disadvantages of reservoir type and ROR type hydropower generation, and hence to assess the economic impact of converting reservoir type hydropower projects to ROR type hydropower projects. Therefore, costs or benefits related to environmental, social and economic impacts of hydropower are considered for the project comparison.

Almost all the major hydropower potential has been captured in Sri Lanka by now. Out of the two existing large ROR type hydropower projects in Sri Lanka, Upper Kotmale Hydropower Project (UKHP) is taken for this research as the case study. However, as there are other hydropower dominant countries in the world with untapped potential, the research outcomes will especially be important to them.

1.2. Literature Review

1.2.1. Identification of research gap

World research related to comparisons between reservoir type and ROR type were studied to identify the research gap.

A study [1] has been conducted focusing on the Amazonian regions of Bolivia, Brazil, Colombia, Ecuador and Peru, which consist of a large untapped hydropower potential, qualitatively compares the reservoir type and ROR type based on the climate change impacts. It says that it will be necessary to invest in reservoirs to increase the margin of reserve and cope with climate change. It also mention the local, social and environmental impacts associated with the exploitation of hydropower. Another study [2] has also been conducted based on the climate change impacts on hydropower, focusing Central and South American regions where 60% of the electricity demand is met through hydropower. Building new storage reservoirs is given in it as a potential adaptation measure in the energy sector.

A review [3] done for Yunnan in China qualitatively compares small and large hydropower projects regarding their environmental implications and socio-economic consequences. A comparison [4] between large and small hydropower projects based in Tibet, based on the CO_2 equivalent has also been done. It says that small hydro performs better in terms of environmentally friendly development and low carbon energy than large hydro in Tibet but large hydro are an essential part to address the huge hydroelectricity demand.

A study [5] from Western Himalayan region of India on environmental sustainability of ROR hydropower projects has been conducted. It presents a public perception cum data collection study on environmental impacts of small and large ROR hydropower projects. It says that every environmental impact of small hydropower is not 'small' as compared to large hydropower and ignoring environmental impacts of small hydropower may not be a good practice in the Himalayan region.

A case study [6] has been conducted for Uma Oya hydropower project in Sri Lanka incorporating socio-environmental considerations into project assessment but GHG emissions from hydropower have not been considered in that.

The identified research gap is an economic comparison between reservoir type and ROR type of the same large hydropower project including the costs related to environmental, social and economic impacts, at the project planning stage for decision making.

1.2.2. Quantification methods of environmental impacts of hydropower

Findings in the last two decades indicate that hydropower reservoirs produce GHG as CO_2 and CH_4, putting into question this generation system as a clean and green electricity source [7],[8]. Most of the past world studies [9],[10],[11],[12],[13] focused on GHG emissions from hydropower reservoirs due to flooded organic matter decaying under water and the quantifications were based on long term field measurements. The results were summarized for tropical and non-tropical regions separately.

Latest research findings on methods of GHG emissions from hydropower and quantification of them were studied because it is an emerging study area at present. A study [8] which combined the ecological impacts with this scenario was found and used for this research. It showed a rough and holistic estimate of net GHG emissions per year in the absence of long term field measurements. It is difficult to estimate the costs related to all ecological impacts of hydropower projects and that research finding covered only deforestation.

2. CASE STUDY – UPPER KOTMALE HYDROPOWER PROJECT

There are many reservoir type large hydropower projects in Sri Lanka [14] but only two large ROR type projects, namely Upper Kotmale Hydropower Project (UKHP) (150MW) and Kukule Ganga Hydropower Project (70MW) are in operation at present. These two were constructed in the recent past, compared to the time period in which the reservoir type projects were done in Sri Lanka. Out of the above two, UKHP was selected as the case study for this research.

2.1. UKHP History and Project Alternatives

According to the feasibility study (F/S) report [15] of UKHP published in 1987, it had to be focused on effective maximum development of hydropower potential during planning of UKHP. The project was based on Kotmale Oya. The optimum upstream dam site was considered to be the Caledonia site which was identified to be ideal for creating a reservoir. Between Caledonia site and the existing Kotmale reservoir, there were good dam sites at Talawakelle, Lindula, Yoxford and Wavahena. Based on those five dam sites, eight alternative development schemes were suggested in the F/S. Out of these, three schemes, which had higher development potential indexes (product of catchment area and total head) [15], had been selected for a detailed comparison. These were Talawakele ROR scheme (123MW), Caledonia reservoir (214MW) and Caledonia/Talawakele two step scheme (248MW).

Comparison of these three development schemes were shown in the F/S report. Only the construction cost, including resettlement cost, was considered in the calculations as cost components. Talawakele ROR showed the best cost effectiveness compared to the other two projects (LKR 0.74/kWh) but it was eliminated from further study as the capacity and the annual generated energy of Talawakele ROR were small compared to the other two projects. Hence the scheme was not preferable from the viewpoint of effective utilization of water resources and hydropower potential. Out of the remaining two projects, Caledonia reservoir was marginally more economically viable (LKR 1.22/kWh) than the Caledonia/Talawakele two step scheme (LKR 1.24/kWh) but again for the same reason and the marginality of the difference, the latter was selected.

According to the EIA report of UKHP published in 1994 [16], there was an engineering services (E/S) study for the project. Three alternative ways were suggested for the selected two step scheme. Simultaneous development of Talawakele and Caledonia, Talawakele with provision for future development of Caledonia, and Talawakele development only, were those. Out of these, the first two were eliminated because of the social impact caused by large number of resettlement (more than 1000 families). Therefore, the third was selected as the optimum scheme and it was a ROR of 150MW. It can be seen that the initial viewpoint of UKHP, which was effective utilization of water resources and hydropower potential [15], was not considered in the decision making there.

As major waterfalls (St. Claire and Devon) were affected from that selected project, another two projects (160MW each) were suggested as two alternatives to that, but they too were economically not feasible. According to the addendum to the EIA report [17] published in 1996, another alternative called Yoxford/Lindula were also suggested due to the same reason, but the study concluded that it was technically not feasible due to very poor geological conditions.

Therefore, the implemented UKHP was Talawakele ROR of 150MW.

2.2. Project Selection for Comparison in this Research Study

The reason for selecting UKHP as the case study for this research, was that there were suggested reservoir type and ROR type project alternatives which were technically and economically feasible as described in section 2.1. Thus, technical and financial data were available for both studies done around the same time.

Instead of UKHP, any other existing hydropower project which does not have both reservoir type and ROR type feasible project alternatives, cannot be selected for this research as the case study. The reason is, if that existing project has only the reservoir type configuration, the researcher has to design a theoretical ROR type for the same project in order to compare under this research and vice versa. Then the problem is, technical feasibility of that theoretical project is not completely ensured because geological conditions of the location matter for civil work and hence stability.

Therefore, the Caledonia reservoir (214MW) and the already implemented Talawakele ROR (150MW) were selected for the comparison under this research considering environmental, social and economic impacts. These projects have ensured technical and economic feasibility.

2.2.1. Project locations

The locations of Caledonia and Talawakele at Kotmale Oya are shown in Figure 2.1. Both are located in Nuwara Eliya District, Central Province with the distance between the two locations of about 10km.

Figure 2.1: Locations of Talawakele and Caledonia

Source: https://mapcarta.com/14844348/Map

2.2.2. Project features

Caledonia reservoir project features were taken from F/S report [15] of UKHP published in 1987. Talawakele ROR project features were taken from an interview with the Project Director. Original information are summarized in Table 2.1.

Project costs [15] given in Table 2.1 included the cost components of civil work and equipment, land acquisition, resettlement, engineering and administration and physical contingency. Caledonia reservoir estimated project cost in 1986 were brought to 2014 level for comparison and it will be discussed in more detail in Chapter 4.

Table 2.1: Project features of Caledonia reservoir and Talawakele ROR

Item	**Caledonia Reservoir**	**Talawakele ROR**
Catchment area (km^2)	235.8	310.6
Dam		
Dam type	concrete gravity	concrete gravity
Dam height (m)	70	34
Reservoir/Pond		
Gross storage capacity (MCM)	45.1	2.5
Effective storage capacity (MCM)	30.0	0.8
Area (km^2)	2.25	0.25
Power Generation		
Rated head (m)	614	473
Maximum turbine discharge (m^3/s)	40.0	36.9
Installed capacity (MW)	214	150
Annual generated energy (GWh)	664	409
Cost		
Project cost (million LKR)	7920 (base year 1986)	53040 (base year 2014)

The original proposal of Talawakele ROR had suggested to take tributary diversions to the main stream (Kotmale Oya) in order to get a larger catchment area. Accordingly, the annual generated energy was originally mentioned as 512GWh in the E/S study in 1995, but five waterfalls were to be impacted due to that proposal. Therefore, all the tributary diversions were cancelled. That resulted in reduction of the annual energy to 409GWh in the implemented Talawakele ROR project.

3. GREENHOUSE GAS EMISSIONS FROM HYDROPOWER

The popular belief that hydropower is a green alternative (with zero GHG emissions) to burning fossil fuels has been found to be wrong [18] especially as hydropower dams produce substantial amounts of carbon dioxide and methane. However, these emissions are reported as 35-70 times less than thermal power plant emissions [19]. The evaluation of greenhouse gas (GHG) emissions from hydropower projects have become very important in the comparison of power generation projects, even among hydropower projects. In this particular study, the GHG comparison is made for two hydro projects using available data at a particular site. Estimation of net GHG emissions per year from the suggested Caledonia reservoir project and implemented Talawakele ROR project of UKHP are described in this chapter.

3.1. GHG Emission Sources and Production

A latest study by Hidrovo *et al* [8] on GHG emissions have accounted for the GHG net reservoir emissions of Hydropower in Ecuador as shown in Figure 3.1.

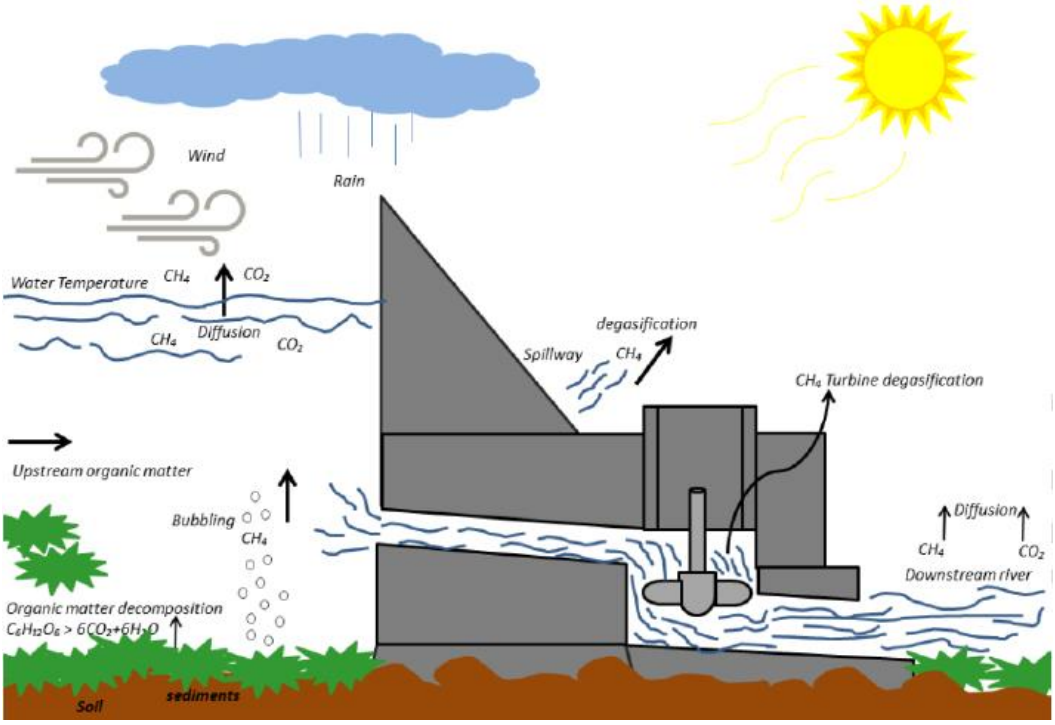

Figure 3.1: GHG Emissions sources from hydropower dams

Source: A.B. Hidrovo *et al.*, Accounting for GHG net reservoir emissions of Hydropower in Ecuador

It shows that in reservoirs/ponds, there are decomposed organic matter like soil and plant material at the basin. These matter are also flooded organic matter and upstream organic matter. These organic matter produce CO_2 and CH_4 which reach the water surface layer and release to the atmosphere by diffusion.

This phenomena has been mentioned by Kumar and Sharma [19] as molecular diffusion at the water-atmosphere interface. As explained in that, the diffusive CO_2 and CH_4 fluxes are dependent on the existence of a concentration gradient between the water and the atmosphere. When the surface water of a reservoir is supersaturated with CO_2 or CH_4 compared to the atmosphere, the gas fluxes occur towards the atmosphere. The opposite of this phenomena also occurs when the surface water is under saturated compared to the atmosphere and then the reservoir surface act as a sink of atmospheric carbon.

CH_4 is also released by bubbling. These bubbles are produced in the methaogenesis process. Less CO_2 bubbles are also produced because CO_2 has a higher solubility than CH_4. This phenomena has been mentioned by Kumar and Sharma [19] as bubbling from the sediment of reservoirs and these bubbles are usually formed under anaerobic conditions. In shallow reservoirs, most of the CH_4 emissions are due to bubbling because CH_4 bubbles are usually dissolved in the water before reaching the water surface in deep reservoirs.

Figure 3.1 also show that GHG are also released to the atmosphere by degasification when the water passes through the spillways of the dam and turbines. This is due to the change of temperature, pressure and turbulence. Kumar and Sharma [19] have mentioned two pathways that do not occur in artificial reservoirs built for other purposes (e.g. irrigation, water supply, flood control and aquaculture). These two pathways are, turbulent degassing of water passing through turbines and degassing downstream of dams.

The water intake from reservoirs to generate electricity is frequently located in medium or lower parts of the dam and hence the water at the deep layers flow through the turbines. Gas (CO_2 and CH_4) solubility is high at deep water layers because mineralization rates and water pressure are high. As found by Kemenes et al

[20], these gases are exposed to high temperature and low pressure which leads to rapid GHG emissions to the atmosphere.

GHG are released to the atmosphere by diffusion in the downstream river. The previously generated turbulence helps the gases to be easily diffused to the air. As observed by Guerin et al, these downstream GHG may be encountered at about 40km from the dam.

These emissions can be precisely determined by long term field measurements.

3.2. Estimation of Net GHG Emissions from Hydropower Projects

Net GHG emissions are the difference between pre and post reservoir emissions from the portion of the river basin which consider GHG exchanges before, during and after the construction of the reservoir [8],[11]. Hidrovo et al said that, in the absence of long term field measurements, a complete, rough and holistic estimate of net GHG emissions per year (E_n) can be obtained from the Equation 3.1[8].

$$E_n = E_e + E_r + E_{tsd} + E_{com} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eq. 3.1$$

Where,

E_e = GHG emissions due to the loss of ecosystem (pre-flooding)

E_r = GHG emissions from reservoir

E_{tsd} = GHG emissions from turbine, spillway and downstream river (post-flooding)

E_{com} = GHG emissions from construction, operation and maintenance

Out of these GHG emission pathways, E_r and E_{tsd} which can be considered as direct emission pathways, were discussed in Section 3.1. In addition to that, indirect emissions as E_e and E_{com} have also been taken into account by Hidrovo et al in developing Equation 3.1. These will be discussed under Section 3.2.1 and 3.2.4.

Especially, the impact on ecosystem due to hydropower projects are important to be considered and accurately estimated because it is another environmental issue. Estimation of loss of ecosystem in GHG emission terms will be discussed under Section 3.2.1.

3.2.1. Estimation of emissions from loss of ecosystem

The formula of photosynthesis and respiration [8], [21] was applied to estimate E_e.

$$CO_2(264g) + H_2O(108g) \rightarrow C_6H_{12}O_6(180g) + O(193g) \rightarrow Amylase(162g) \ldots\ldots Eq. 3.2$$

In the photosynthesis process, plants absorb CO_2 and water and with the use of energy from sunlight plants produce glucose ($C_6H_{12}O_6$), oxygen and amylase [8]. The particular element called amylase is related to growth of dry matter in a plant. According to the formula given in Equation 3.2, to produce 1g of dry matter, it is required to absorb 1.63g CO_2. Therefore, if the dry matter weight of a plant is known, the amount of CO_2 which will not be absorbed from the atmosphere due to the loss of that plant can be calculated. In other words, it is the amount of GHG emission due to the loss of ecosystem or deforestation.

Dry matter weight of a plant type can be obtained from its Net Primary Production (NPP) data [8]. NPP is obtained of Gross Primary Production (GPP). Chapman et al [22] defined GPP, NPP and plant respiration as follows. GPP is the measure of total amount of dry matter made by a plant in photosynthesis, while NPP is the difference between GPP and autotrophic respiration. During respiration, some of the matter from GPP is converted back into CO_2 and water, and dry weight is therefore lost.

NPP values used for this research are given in Table 3.1. NPP of tea plantations was assumed to be that of the available cultivated land data in literature.

Table 3.1: NPP of tropical forest and cultivated land

Land Type	**NPP (g dry matter/m^2/year)**
Tropical forest	1500
Cultivated land	650

Source: http://www.ebooklibrary.org/articles/eng/Primary_production

Used land types of the two projects are given in Table 3.2. In literature, Hidrovo et al [8] considered land use only of the reservoir. In this study, all the significant land usages were taken into account.

Table 3.2: Land use of Caledonia reservoir and Talawakele ROR projects

Land Use	Caledonia Reservoir Project		Talawakele ROR Project	
	Land Type	Area (ha)	Land Type	Area (ha)
Dam site and reservoir	Tea	232	Tea	33.8
Resettlement area	Tea	368	Tea	26.2
Power house and switchyard	Tea	15	Forest	14.2

- Loss of dry matter production due to loss of tea plantations in Caledonia reservoir project = 650 g $m^{-2}yr^{-1} \times (232+368+15) \times 10^4$ m^2
  = 3997.5 ton/year

  Hence, E_e = 1.63 × 3997.5 ton CO_2/year
  = 6516 ton CO_2/year

- Loss of dry matter production due to loss of tea plantations and forest in Talawakele ROR project = 650 g $m^{-2}yr^{-1} \times (33.8+26.2) \times 10^4$ m^2 + 1500 g $m^{-2}yr^{-1} \times (14.2) \times 10^4$ m^2
  = 603 ton/year

  Hence, E_e = 1.63 × 603 ton CO_2/year
  = 983 ton CO_2/year

3.2.2. Estimation of emissions from reservoir

GHG emissions due to the decaying organic matter under water was estimated using Eq. 3.2 [4],[8].

$$E_r = E_f \times A_e \quad \ldots\ldots\ldots \quad Eq. 3.2$$

Where,

E_f = Mean reservoir emission factor

A_e = Area of reservoir/pond

Following long term field measurements data, past studies [8],[11],[12] have plotted reservoir GHG emissions against hydropower plant lifetime, which are decaying exponential variations. As mentioned by Demarty and Bastien [11], degradation of flooded organic matter is the main source of reservoir GHG emissions during the first 10 years after reservoir creation, in Petit Saut (French Guiana) reservoir. After 10 years, the reservoir emissions are related to the organic matter entering the system and therefore this emission is quite stable during the lifetime of the reservoir. Similarly, stable emissions have been shown after 12 years in Brazil's Tucurui reservoir and after 18 years in Brazil's Balbina reservoir [8]. Out of them, Petit Saut and Tucurui are in tropical zones.

According to Zhang et al [4], it is almost impossible to determine this reservoir GHG emissions precisely in the absence of long term field measurements. Therefore, Zhang et al has applied directly a constant mean reservoir emission factor for the total power plant lifetime, based on the literature. GHG emissions by the decaying process depend on the local geography and climate. Therefore, reservoir GHG emissions for tropical and boreal regions were reviewed separately in that study. It showed that, boreal regions have a significantly lower GHG emissions than tropical regions.

Sri Lanka is a tropical country and also has not done long term field measurements yet. Therefore, constant mean E_f of tropical regions was selected for this research for the total power pant lifetime.

$$\text{Tropical } E_f = 2771.6 \text{ g } CO_2\text{-eq m}^{-2}\text{yr}^{-1} \text{ [4]}$$

As explained by Kumar and Sharma [19], the solubility of CO_2 and CH_4 in water causes for the amount of GHG flow through the water-atmosphere interface. Therefore, GHG emissions through diffusion is higher in reservoirs located in warmer regions and at lower altitudes.

A_e of Caledonia reservoir and Talawakele pond are given in Table 3.3.

Table 3.3: Caledonia reservoir and Talawakele pond areas

Reservoir/Pond	**Area (km^2)**
Caledonia reservoir	2.25
Talawakele pond	0.25

- E_r from Caledonia reservoir = 2771.6 g CO_{2}-eq $m^{-2}yr^{-1} \times 2.25\times10^{6}$ m^2

  = 6236 ton CO_{2}-eq/year

- E_r from Talawakele pond = 2771.6 g CO_{2}-eq $m^{-2}yr^{-1} \times 0.25\times10^{6}$ m^2

  = 693 ton CO_{2}-eq/year

It should be noted that there may be differences between reservoir and ROR pond water behaviour. Water is always stored in the reservoir but in Talwakele pond water is collected during the day time and used during the night peak hours. This may affect reservoir/pond GHG emission patterns.

3.2.3. Estimation of emissions from turbine, spillway & downstream river

According to Hidrovo et al, out of the total direct GHG emissions (E_r and E_{tsd}), 45% would come from the reservoir and 55% would come from turbine, spillway and downstream. Therefore, E_{tsd} was determined by Eq.3.3 [8].

$$E_{tsd} = \frac{E_r \times 55}{45} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eq. 3.3$$

- E_{tsd} from Caledonia reservoir project

  = 6236 ton CO_{2}-eq/year × (55/45)

  = 7622 ton CO_{2}-eq/year

- E_{tsd} from Talawakele ROR project

  = 693 ton CO_{2}-eq/year × (55/45)

  = 847 ton CO_{2}-eq/year

3.2.4. Estimation of emissions from construction, operation & maintenance

As explained by Hidrovo et al [8], Life Cycle Impact Assessment (LCIA) is an internationally accepted tool which allows to identify the potential environmental impacts associated with a product or service, throughout its entire lifespan. A LCIA was performed by Hidrovo et al to determine E_{com}.

For this research, LCIAs performed for reservoir type and ROR type hydropower projects were studied from literature. E_{com} values were estimated accordingly.

- E_{com} of Caledonia reservoir project

Turconi et al [23] did a critical review of case studies involving LCIA of electricity generation from hydropower and found that E_{com} was in the value range of 11-20 kg CO_2-eq/MWh for dam reservoirs. Zhang et al [24] used LCIA to compare two reservoir hydropower schemes, one with a concrete gravity dam (CGD) and the other with an earth-core rockfill dam (ECRD). It was found that the CGD scheme had a higher E_{com} (11.11 kgCO_2-eq/MWh) than ECRD.

Caledonia reservoir also has a CGD and hence the best possible approximation of E_{com} for Caledonia was made as 11 kgCO_2-eq/MWh.

Total E_{com} = (11 kgCO_2-eq/MWh) × 664 × 10^3 MWh

= 7304 ton CO_2-eq/year

- E_{com} of Talawakele ROR project

H. Hondo [25] performed LCIA for ROR type hydropower projects and found that a ROR (plant life: 30 years, plant factor: 45%) with small reservoir had E_{com} value as 11 kgCO_2-eq/MWh. The variation of that with plant life and plant factor is given as shown in Table 3.4 and Table 3.5.

Table 3.4: Effects of lifetimes on E_{com}

Lifetime (years)	10	20	30 (reference)	50	100
E_{com} (kgCO_2-eq/MWh)	30	16	11	8	5

Source: H. Hondo, Life cycle GHG emission analysis of power generation systems: Japanese case

Talawakele ROR has a plant life of 50 years. Therefore, E_{com} value was approximated as 8 kgCO_2-eq/MWh which was a reduction by 3 kgCO_2-eq/MWh than the reference.

Table 3.5: Effects of plant factors on E_{com}

Plant factors (%)	-10pts	-5pts	45 (reference)	+5pts	+10pts
kgCO_2-eq/MWh	14	13	11	10	9

Source: H. Hondo, Life cycle GHG emission analysis of power generation systems: Japanese case

Talawakele ROR has a plant factor of 30% and hence the values in Table 3.5 were plotted to obtain E_{com} at that plant factor.

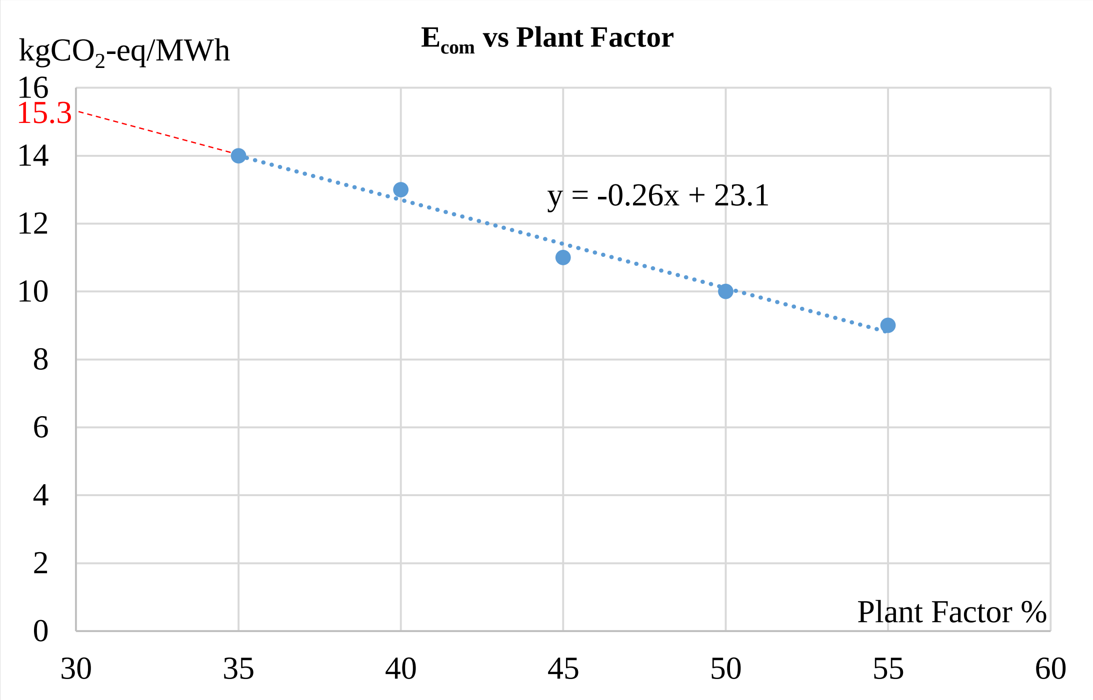

Figure 3.2: Variation of E_{com} with plant factor in a ROR scheme with small reservoir

According to the plot in Figure 3.2, Talawaele ROR E_{com} value was extrapolated as 15.3 kgCO_2-eq/MWh. Therefore, there was an increase of E_{com} by 4 kgCO_2-eq/MWh than the reference.

Based on the above findings, it was approximated that E_{com} of Talawakele ROR project as 12 kgCO_2-eq/MWh, with 50 plant life and 30% plant factor.

Total E_{com} = (12 kgCO_2-eq/MWh) × 409 × 10^3 MWh

= 4908 ton CO_2-eq/year

3.2.5. Total emissions

E_n of Caledonia reservoir project and Talawakele ROR project were calculated using Eq. 3.1 and given in Table. 3.6.

Table 3.6: Net GHG emissions (E_n) per year

Parameter	Caledonia Reservoir Project (ton CO_2-eq/year)	Talawakele ROR Project (ton CO_2-eq/year)
E_e	6516	983
E_r	6236	693
E_{tsd}	7622	847
E_{com}	7304	4908
E_n	27678	7431

The estimated total GHG emissions per year from Caledonia reservoir project was approximately four times than Talawakele ROR project.

The specific GHG emissions of the two hydropower projects are summarized in Table 3.7 below.

Table 3.7: Specific GHG emission

Hydropower Project	Annual Energy (GWh)	Annual Total GHG Emission (ton CO_2-eq)	Specific GHG Emission (g CO_2-eq /kWh)
Caledonia reservoir type	664	27678	41.68
Talawakele ROR type	409	7431	18.17

Accordingly it can be seen that even the GHG emissions from reservoir type hydropower projects are negligible compared to that of thermal power projects where specific GHG emissions are several hundred grams per kWh.

4. ECONOMIC COMPARISON OF SELECTED HYDROPOWER PROJECTS

When decision making on selecting a project among several project alternatives, technical feasibility and economic viability are two important factors to be considered in engineering projects. The technical feasibilities of the two selected projects for comparison in this research were ensured from their feasibility study reports as discussed under Chapter 2. Therefore, the decision making will be based on their economic viability.

4.1. Levelized Cost of Electricity

Levelized Cost of Electricity (LCOE) which is a convenient summary measure of the overall competitiveness of different generating technologies [26] will be separately calculated for Caledonia reservoir and Talawakele ROR projects under this chapter. In general, LCOE includes the initial capital costs, fuel costs (if any), fixed and variable operation & maintenance (O&M) costs, financing costs, and the discount rate [26]. LCOE is a useful tool because it can combine both the fixed costs and variable costs into a single measure to simplify analysis.

According to the Eq. 4.1, the LCOE is defined as the ratio of the Net Present Value (NPV) of total costs of a generic plant to the NPV of the net electricity generated by the plant over its operating life [26].

$$LCOE = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Output} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq\ 4.1$$

Where,

I_t = Investment and expenditures for the year (t)

M_t = Operational and maintenance expenditures for the year (t)

F_t = Fuel expenditures for the year (t)

E_t = Electrical output for the year (t)

r = Discount rate

n = (expected) Lifetime of the power system

F_t is irrelevant to hydropower projects and hence it was eliminated in this study. The parameters considered to calculate LCOE for Caledonia reservoir and Talawakele ROR projects were,

- Capital repayment (loan)
- Finance cost (loan interest)
- Plant O&M cost
- Benefit from Carbon trading under Clean Development Mechanism (CDM)
- Discount rate (assumption 10%)
- Plant lifetime (50 years)
- Annual energy generation of Caledonia reservoir and Talawakele ROR projects (664GWh and 409GWh respectively)

4.2. Loan Details

Power generation projects in Sri Lanka receive loans from international donors. Loan details of the implemented Talawakele ROR project were available and given in Table 4.1. The same conditions were assumed for Caledonia reservoir project.

Table 4.1: Loan details of the Talawakele ROR project

Parameter	Loan Details
Donor	Japan International Cooperation Agency (JICA)
Signed year	2003
Grace period	10 years
Loan repayment period	30 years
Average interest rate	0.93% on Japanese Yen (JPY)
Adjusted interest rate	10.65% on Sri Lankan Rupees (LKR)

4.2.1. Loan interest rate

The original loan interest was mentioned as 0.95% for the contract and 0.75% for the consultancy. That consultancy component was around 10% of the loan. Therefore, the weighted average (0.93%) was taken for this study. As the capital repayments and interest payments (in LKR) started after 10 years (2013), the 0.93% interest rate was adjusted by calculating as given below.

Average loan interest rate (on JPY) = 0.0093

Average JPY to LKR exchange rate (from 2003 to 2013) = 1.13

Average inflation rate in Sri Lanka (from 2003 to 2013) = 0.0960

Adjusted loan interest rate (on LKR) = $(0.0093\times1.13)+0.0960$

= 10.65%

To calculate the average, JPY to LKR foreign currency exchange rates and inflation rates were obtained from Central Bank of Sri Lanka (CBSL). Those were attached under Appendix A.

4.2.2. Project cost and loan amount

The project cost and the loan amount of the implemented Talawakele ROR project on actual basis were calculated from the annual cost distribution data during the construction period. It was attached under Appendix B. The calculated result summary was given in Table 4.2.

Table 4.2: Project cost and loan amount of Talawakele ROR project on actual basis

Parameter	Value
Project cost (base year 2014) (million LKR)	53040
Original loan amount (million LKR)	47251
Loan as a percentage from project cost (%)	89
Adjusted loan amount at the end of grace period (million LKR)	51834

During the grace period, the Government of Sri Lanka (GOSL) was released from capital repayments and interest payments. Therefore, the original loan amount was adjusted to get the new loan amount at the end of the grace period, by calculating as given below.

Adjusted loan amount (million LKR) = $47251 \times (1+0.0093)^{10}$

= 51834

The project cost of Caledonia reservoir was taken from the F/S report [15]. The percentage of the original loan amount from the project cost was assumed as 89% to maintain the same conditions in both projects for comparison. Those information summary was given in Table 4.3.

Table 4.3: Project cost and loan amount of Caledonia reservoir project

Parameter	Value
Project cost (base year 1986) (million LKR)	7920
Adjusted project cost in 2014 (million LKR)	116860
Original loan amount (million LKR)	104005
Adjusted loan amount at the end of grace period (million LKR)	114092

Using average inflation rate in Sri Lanka from 1986 to 2014, which was 10.09%, the original project cost of Caledonia reservoir was adjusted to 2014 to maintain the same conditions in both projects for comparison. The calculation is given in Appendix C.

Original loan amount (million LKR) $= 116860 \times 89\%$

$= 104005$

Adjusted loan amount (million LKR) $= 104005 \times (1+0.0093)^{10}$

$= 114092$

4.2.3. Loan schedules

Two loan schedules were prepared for Talawakele ROR and Caledonia reservoir projects separately, considering the 30 years of loan repayment period. These were attached under Appendix D and E respectively. The purpose of loan schedules was to obtain the cash outflow from capital repayments and interest payments (finance cost) to use for LCOE calculations.

4.3. Plant Operation & Maintenance Cost

Actual O&M costs of the implemented Talawakele ROR type hydropower plant were obtained for year 2014, 2015 and 2016. The plant was commissioned on 14th July 2012 [27] and the O&M cost could be exactly obtained since 2014. Those annual O&M cost values were given in Table 4.4.

Table 4.4: O&M cost of Talawakele ROR type hydropower plant

Year	O&M Cost (million LKR)
2014	114
2015	140
2016	160

In order to calculate the LCOE, the O&M costs of the plant for its lifetime were required. It was obtained by plotting the O&M cost variation as shown in Figure 4.1.

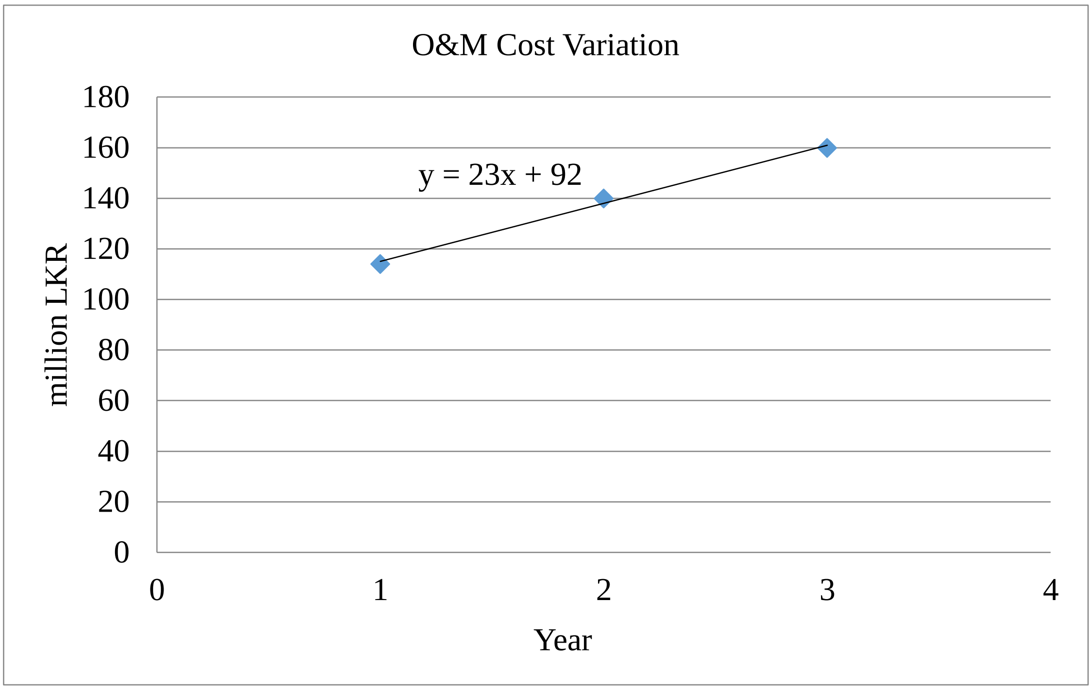

Figure 4.1: O&M cost variation of Talawakele ROR type hydropower plant

O&M costs of Caledonia reservoir type hydropower plant were assumed to be proportionate to the plant capacity and hence the calculation of those were based on the O&M costs of Talawakele ROR type hydropower plant. A sample calculation was given below.

O&M cost of Caledonia reservoir plant in 2014 (million LKR)

$$= (23\times1 + 92) \times (214/150)$$

$$= 164$$

4.4. Benefits under Clean Development Mechanism

As GHG emissions from hydropower projects were estimated in Chapter 3, CDM benefit calculations were done in this study.

4.4.1. Carbon trading

Carbon trading, which is also called Clean Development Mechanism (CDM), is a new international market introduced by the Kyoto Protocol (KP) as a global strategy to combat global warming [28]. Considering the fact that the developed or industrialized countries contribute to high levels of GHG emissions, KP has given mandatory emission reduction targets to them. There are no such legal commitments under KP for developing countries. These developing countries can implement projects, which reduce GHG emissions to the atmosphere or absorb GHG from the atmosphere. These reduced or absorbed amount of GHG can be purchased by developed countries to achieve their mandatory emission reduction targets. This is called as CDM or carbon trading [28].

KP entered into force in 2005 and its first commitment period was from 2008 to 2012 [29]. The highest carbon trading prices (in Euro/ton CO_2) were shown from 2005 to 2012 period [30]. KP failed due to high GHG emissions from later industrialized developing countries such as India and China, which were initially not members of KP. After that, Doha amendment to the KP was made and the second commitment period started from January 2013 and it will end in December 2020 [29]. Lower carbon trading prices were shown from January 2013 to up to now [30], possibly as a result of the failure of KP. After KP will be over in 2020, the Paris Agreement will come into effect [29] and hence it can be assumed that carbon trading prices will increase again.

In this study, the average carbon trading price from August 2005 to November 2017 were calculated as Euro11.87/ton CO_2. Average Euro to LKR exchange rate for the same period was calculated based on the CBSL data (1 Euro = LKR155.48). These data were given in Appendix F and G. The converted average carbon trading price which was LKR 1845.58/ton CO_2 was taken for the calculations in this study.

As estimated in Chapter 3, total GHG emissions from Caledonia reservoir project was 27678 ton CO_2-eq/year and it was 7431 ton CO_2-eq/year from Talawakele ROR project. If UKHP was implemented under CDM, the GHG emission reduction compared to baseline emissions defined for CDM projects, could have been sold via carbon trading and get an income. In this study, that was considered as benefits of both projects.

Grid Emission Factor (GEF) is a parameter to determine the baseline emissions for CDM projects in the renewable energy sector and waste heat/gas recovery sector. It refers to CO_2 emission factor associated with each unit of electricity provided by an electricity system [31]. The last updated GEF (in 2016) of Sri Lanka was taken for the calculations in this study.

GEF in Sri Lanka = 0.8199 ton CO_2/MWh [32]

GHG emission reduction from Caledonia reservoir project compared to CDM baseline emissions = $(0.8199 \times 664 \times 10^3 - 27678)$ ton CO_2/year

= 516,735.60 ton CO_2/year

Hence, CDM benefit (million LKR/year)

= (LKR1845.58/tonCO_2)×516,735.60tonCO_2/year

= 953.68

GHG emission reduction from Talawakele ROR project compared to CDM baseline emissions = $(0.8199 \times 409 \times 10^3 - 7431)$ ton CO_2/year

= 327,908.10 ton CO_2/year

Hence, CDM benefit (million LKR/year)

= (LKR1845.58/tonCO_2)× 327,908.10 tonCO_2/year

= 605.18

4.5. Levelized cost of electricity calculation & economic comparison

Two cash outflows were prepared and hence NPV of total costs and NPV of energy were calculated considering the lifetime of the plants. The cash flows were attached under Appendix H and I. The result summary was given in Table 4.5.

Table 4.5: LCOE calculation summary

Parameter	Caledonia Reservoir Project	Talwakele ROR Project
NPV (Costs)	101,242.30	45,300.15
NPV (Energy)	6,583.44	4,055.16
LCOE (LKR/kWh)	15.38	11.17

As shown in Table 4.5, the unit cost of electricity generation of Talawakele ROR was substantially lower than that of Caledonia reservoir although its annual energy generation was higher than Talawakele ROR.

5. NATIONAL BENEFIT

Hydropower plants are quite often used to serve the peak load, as the amount of power transfer can be changed quite quickly. As UKHP is a peak serving plant, an additional comparison was done between Caledonia reservoir and Talawakele ROR, considering their peak operation ability, in this study and discussed in this chapter.

Reservoirs can store water and hence the expected operation during peak hours can be obtained in both dry seasons and wet seasons of a year. In ROR, the flowing water is collected and stored during the day time in dry seasons in order to operate during the night peak. The expected peak operation may not always be possible because the stored water amount may not be sufficient to cover the whole peak period.

- Caledonia reservoir type hydropower plant

Installed capacity = 214

Annual energy (GWh) = 664

LCOE (LKR/kWh) = 15.38

No. of night peak hours per day (6.30pm-10.30pm) = 4

Annual night peak generation (GWh) = $214 \times 4 \times 365 \times 90\% \times 10^{-3}$

= 281

Note: It was assumed that plant maintenance period as 10% of the year

Annual cost of generation during night peak (LKR million) = 281×15.38

= 4322

Annual thermal plant operation cost in the absence of Caledonia reservoir hydropower plant (million LKR) = 32.34×281

= 9088

According to the System Control Centre (SCC) data given under Appendix J, LKR 32.34/kWh is the current unit cost of electricity generation of GT7 machine in Kelanitissa Power Station (KPS). It is the highest cost thermal power plant next to the KPS small GT machines (LKR 51.17/kWh). Both are at the bottom of the SCC plant dispatch order. Out of the two, GT7 operation cost was taken for the calculations in this study because more generation from GT7 had been shown in the past years than small GT machines [33],[34],[35],[36],[37].

Annual cost saving by Caledonia reservoir hydropower plant operation (LKR million) = 9088 - 4322

= 4766

Similar calculations were done for Talawakele ROR hydropower plant. The results were given below.

- Case 1: assumed rated operation during the total night peak period of a year,

  Annual night peak energy (GWh) = 197

  Annual cost saving (LKR million) = 4171

- Case 2: based on the actual operation data of UKHP obtained from SCC,

Table 5.1: Night peak generation of UKHP on actual basis and cost savings

Year	Night Peak Generation (GWh)	Annual Cost Saving (LKR million)
2014	172	3641
2015	187	3959
2016	146	3091
2017 (up to September)	83	1757

SCC daily recorded the maximum output (MW) of UKHP during the night peak operation and the time it occurred. It was attached under Appendix K. In this study, it was assumed that the plant operated with that output for the total night peak period in the respective days. This assumption was made due to the information availability. Accordingly, the generated night peak energy were calculated for each year from 2014 to 2017 as shown in Table 5.1.

As mentioned in Chapter 2, the initial concept of UKHP during its planning stage, was the effective utilization of water resources and hydropower potential. The reason was the peak serving capability. Therefore, the following results showed a loss to the country by energy reduction due to not using the potential for reservoir type.

Case 1 scenario

Annual (LKR million) = 4766 – 4171 = 595

In 2017 up to September (LKR million) = 595 × 0.75 = 446

According to the results shown in Case 1, even though the Talwakele ROR hydropower plant operates in its full capacity (assuming every year is a wet year), there is a loss to the country. Case 2 results showed the loss on actual basis.

Case 2 scenario

In 2014 (LKR million) = 4766 - 3641 = 1125

In 2015 (LKR million) = 4766 - 3959 = 807

In 2016 (LKR million) = 4766 - 3091 = 1675

In 2017 up to September (LKR million) = (4766× 0.75) – 1757

= 1818

The comparison of Case 1 and Case 2 scenarios are given in Table 5.2 considering per year basis from 2014 to 2017 September.

Table 5.2: Financial loss comparison based on rated and actual operation of Talawakele ROR project

Year	**Case 1: Rated Operation (LKR million)**	**Case 2: Actual Operation (LKR million)**
2014	595	1125
2015	595	807
2016	595	1675
2017 (up to September)	446	1818
Total Loss	2231	5425

6. CONCLUSIONS AND RECOMMENDATIONS

The economic comparison, between reservoir type and ROR type hydropower plants, was performed in this study considering UKHP as the case study. The already implemented Talwakele ROR and an earlier suggested Caledonia reservoir projects were selected for the comparison.

Environmental impacts estimation, based on the available data on GHG emissions, was the key study area in this research. The results show that the GHG emissions from Caledonia reservoir project is approximately four times higher than that of Talawakele ROR project. However, the specific GHG emission from both versions are very low compared to any type of thermal power plant. Therefore, it is concluded that GHG emission considerations are not strong enough to discourage any type of new hydropower plant developments.

In the economic analysis, capital repayments, finance cost, plant O&M cost, CDM benefits and annual electricity generation were used to calculate LCOE for the both projects considering the whole plant lifetime. The results show that the LCOE of Talawakele ROR project is substantially lower than that of Caledonia reservoir project. As UKHP was designed as a peak serving plant, an additional analysis was done considering the night peak operation of both plants. The results show that there is a loss to the country by energy reduction due to not using the full potential for the reservoir type.

According to the LCOE results, it can be concluded that the ROR type has the overall economic benefit in the case of UKHP, but if the project objective is solely to capture the maximum hydropower potential in the area or peak serving, it can be concluded that the reservoir type has a better overall economic benefit to the country.

It is recommended that for similar future large hydropower developments, a detailed similar study to be carried out before taking the decision on reservoir construction for hydropower generation. A case by case study is recommended to be conducted because the environmental factors to be considered vary according to the location such as the impact of flooding, melting snow and ice, etc. The methodology presented in this study can be followed by such studies with suitable modifications where necessary.

In the absence of long term field measurements, a methodology which gives a rough and holistic estimate of GHG emissions from hydropower projects was used in this research. Therefore, it is recommended to do field measurements and obtain a higher accuracy GHG emission database for Sri Lankan major hydropower projects. It important because other countries have already measured and have proven evidences for their GHG amounts.

Although hydropower projects do not have zero GHG emissions, they are much less GHG emitters compared to thermal power plants. Therefore, many large scale hydropower projects are recommended to be implemented capturing all possible hydropower potential in the world.

The overall economics for the decision on whether to implement a ROR type hydropower project instead of a reservoir type hydropower project will depend upon the additional cost of the reservoir and the benefits of the reservoir project such as ability to collect water from wet season to dry season, rather than GHG emissions caused by reservoirs.

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APPENDIX – A: JPY to LKR Exchange Rate and Inflation Rate in Sri Lanka

Year	Annual Average Exchange Rates (JPY to LKR)
2003	0.83
2004	0.94
2005	0.91
2006	0.89
2007	0.94
2008	1.05
2009	1.23
2010	1.29
2011	1.39
2012	1.60
2013	1.32
2014	1.24
2015	1.12
2016	1.34
2017	1.36

Year	Annual Average Inflation Rate (%)
1986	8.00
1987	7.70
1988	14.00
1989	11.60
1990	21.50
1991	12.20
1992	11.40
1993	11.70
1994	8.40
1995	7.70
1996	15.90
1997	9.60
1998	9.40
1999	4.70
2000	6.20
2001	14.20
2002	9.60
2003	6.30
2004	9.00
2005	11.00
2006	10.00
2007	15.80
2008	22.60
2009	3.50
2010	6.20
2011	6.70
2012	7.60
2013	6.90
2014	3.30
2015	0.93
2016	3.75

Source: Central Bank of Sri Lanka

APPENDIX – B: Project Cost and Loan Distribution of UKHP on Actual Basis

Year	in JPY			in LKR		
	Total Cost (million JPY)	Loan (million JPY)	Others (million JPY)	Total Cost (million LKR)	Loan (million LKR)	Others (million LKR)
2002	0	0	0	0	0	0
2003	536	453	83	447	378	69
2004	211	178	33	197	166	31
2005	832	703	129	761	643	118
2006	2628	2220	408	2349	1984	365
2007	4181	3531	650	3932	3321	611
2008	6687	5647	1040	7028	5935	1093
2009	5257	4210	1047	6470	5181	1289
2010	5776	5077	700	7447	6546	902
2011	6744	6395	350	9355	8871	486
2012	5607	5323	284	8967	8513	454
2013	1547	1362	185	2049	1804	245
2014	3265	3163	102	4035	3909	126
Total	43271	38262	5011	53040	47251	5789

APPENDIX – C: Caledonia Reservoir Project Cost Conversion from 1986 to 2014

Original project cost (base year 1986) : LKR 7920 million

Average inflation rate from 1986 to 2014: 10.09%

Year	Adjusted Project Cost (LKR million)
1987	8719
1988	9599
1989	10567
1990	11634
1991	12808
1992	14100
1993	15522
1994	17089
1995	18813
1996	20711
1997	22801
1998	25101
1999	27634
2000	30423
2001	33492
2002	36872
2003	40592
2004	44688
2005	49197
2006	54160
2007	59625
2008	65641
2009	72265
2010	79556
2011	87583
2012	96421
2013	106149
2014	116860

APPENDIX – D: Loan Schedule of Talawakele ROR Project

Loan schedule (in million LKR) of Talwakele ROR project at 10.65% interest rate.

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Opening Balance	51834	50106	48378	46651	44923	43195	41467	39739	38012	36284	34556	32828	31100	29373	27645
Interest	5428	5244	5060	4876	4692	4508	4324	4140	3956	3772	3588	3404	3220	3036	2852
Loan Repayment	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728
Closing Balance	50106	48378	46651	44923	43195	41467	39739	38012	36284	34556	32828	31100	29373	27645	25917
Year	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**
Opening Balance	25917	24189	22461	20734	19006	17278	15550	13822	12095	10367	8639	6911	5183	3456	1728
Interest	2668	2484	2300	2116	1932	1748	1564	1380	1196	1012	828	644	460	276	92
Loan Repayment	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728	1728
Closing Balance	24189	22461	20734	19006	17278	15550	13822	12095	10367	8639	6911	5183	3456	1728	0

APPENDIX – E: Loan Schedule of Caledonia Reservoir Project

Loan schedule (in million LKR) of Caledonia reservoir project at 10.65% interest rate.

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Opening Balance	114092	110289	106486	102683	98880	95077	91274	87471	83668	79865	76062	72259	68455	64652	60849
Interest	11948	11543	11138	10733	10328	9923	9518	9113	8708	8303	7898	7493	7088	6683	6278
Loan Repayment	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803
Closing Balance	110289	106486	102683	98880	95077	91274	87471	83668	79865	76062	72259	68455	64652	60849	57046

Year	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
Opening Balance	57046	53243	49440	45637	41834	38031	34228	30425	26622	22818	19015	15212	11409	7606	3803
Interest	5873	5468	5063	4658	4253	3848	3443	3038	2633	2228	1823	1418	1013	608	203
Loan Repayment	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803	3803
Closing Balance	53243	49440	45637	41834	38031	34228	30425	26622	22818	19015	15212	11409	7606	3803	0

APPENDIX – F: Carbon Trading Price Variation in the World

Month	Euro/ tonCO2	Month	Euro/ tonCO2	Month	Euro/ ton CO2	Month	Euro/ ton CO2
17-Nov	7.53	14-Sep	6.06	11-Jul	16.25	08-Jan	19.10
17-Oct	7.37	14-Aug	6.73	11-Jun	18.46	7-Dec	22.41
17-Sep	7.07	14-Jul	6.57	11-May	22.27	7-Nov	22.35
17-Aug	5.94	14-Jun	6.25	11-Apr	22.90	7-Oct	22.27
17-Jul	5.23	14-May	5.48	11-Mar	22.63	7-Sep	21.68
17-Jun	5.03	14-Apr	5.90	11-Feb	19.90	7-Aug	19.40
17-May	4.98	14-Mar	5.08	11-Jan	19.03	7-Jul	21.15
17-Apr	4.57	14-Feb	7.86	10-Dec	18.16	7-Jun	0.12
17-Mar	4.69	14-Jan	6.11	10-Nov	19.14	7-Mar	1.26
17-Feb	5.24	13-Dec	5.33	10-Oct	19.15	7-Jan	2.30
17-Jan	5.36	13-Nov	4.89	10-Sep	20.14	6-Dec	6.45
16-Dec	6.57	13-Oct	5.39	10-Aug	19.90	6-Nov	8.10
16-Nov	4.61	13-Sep	5.67	10-Jul	14.13	6-Oct	11.00
16-Oct	5.93	13-Aug	5.08	10-Jun	15.19	6-Sep	12.85
16-Sep	4.99	13-Jul	4.87	10-May	15.15	6-Aug	15.80
16-Aug	4.47	13-Jun	4.74	10-Apr	15.95	6-Jul	16.05
16-Jul	4.43	13-May	4.51	10-Mar	12.82	6-Jun	15.65
16-Jun	4.47	13-Apr	3.54	10-Feb	12.86	6-May	17.05
16-May	6.10	13-Mar	5.46	10-Jan	12.71	6-Apr	13.30
16-Apr	6.18	13-Feb	5.59	09-Dec	12.31	6-Mar	26.95
16-Mar	5.22	13-Jan	3.97	09-Nov	13.14	6-Feb	25.95
16-Feb	5.01	12-Dec	7.69	09-Oct	14.54	6-Jan	26.05
16-Jan	6.07	12-Nov	7.65	09-Sep	13.36	5-Dec	21.10
15-Dec	8.29	12-Oct	9.89	09-Aug	14.89	5-Nov	19.60
15-Nov	8.65	12-Sep	9.71	09-Mar	11.45	5-Oct	21.95
15-Oct	8.71	12-Aug	10.04	09-Feb	9.96	5-Sep	22.65
15-Sep	8.23	12-Jul	8.67	09-Jan	11.57	5-Aug	23.65
15-Aug	8.16	12-Jun	10.38	08-Dec	15.45		
15-Jul	7.96	12-May	8.13	08-Nov	15.52		
15-Jun	7.54	12-Apr	9.77	08-Oct	17.94		
15-May	7.44	12-Mar	9.34	08-Sep	22.35		
15-Apr	7.51	12-Feb	11.87	08-Aug	25.19		
15-Mar	7.05	12-Jan	10.92	08-Jul	22.06		
15-Feb	7.25	11-Dec	9.92	08-Jun	28.77		
15-Jan	7.28	11-Nov	11.38	08-May	26.10		
14-Dec	7.48	11-Oct	13.77	08-Apr	23.88		
14-Nov	7.29	11-Sep	14.42	08-Mar	22.27		
14-Oct	6.59	11-Aug	17.17	08-Feb	21.31		

Source: https://www.investing.com/commodities/carbon-emissions-historical-data

APPENDIX – G: Euro to LKR Exchange Rates

Year	Average EURO to LKR Rate
2005	125.10
2006	130.63
2007	151.63
2008	159.32
2009	160.21
2010	150.10
2011	153.86
2012	164.01
2013	171.51
2014	173.47
2015	150.84
2016	161.16
2017	169.46

Source: Central Bank of Sri Lanka

APPENDIX – H: Energy and Cash Outflow of Talawakele ROR Project (costs & benefits are given in million LKR)

Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Energy (GWh)	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00
O&M Cost	69.00	92.00	115.00	138.00	161.00	184.00	207.00	230.00	253.00	276.00	299.00
Finance Cost	0.00	5428.32	5244.31	5060.30	4876.29	4692.28	4508.27	4324.25	4140.24	3956.23	3772.22
Capital Repayments	0.00	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80
CDM Benefit	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18
Total Costs	**-536.18**	**6642.94**	**6481.93**	**6320.92**	**6159.91**	**5998.90**	**5837.89**	**5676.88**	**5515.86**	**5354.85**	**5193.84**

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**
Energy (GWh)	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00
O&M Cost	322.00	345.00	368.00	391.00	414.00	437.00	460.00	483.00	506.00	529.00	552.00
Finance Cost	3588.21	3404.20	3220.19	3036.18	2852.17	2668.16	2484.15	2300.14	2116.12	1932.11	1748.10
Capital Repayments	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80
CDM Benefit	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18
Total Costs	**5032.83**	**4871.82**	**4710.81**	**4549.80**	**4388.79**	**4227.78**	**4066.77**	**3905.76**	**3744.75**	**3583.73**	**3422.72**

Year	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**
Energy (GWh)	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00
O&M Cost	575.00	598.00	621.00	644.00	667.00	690.00	713.00	736.00	759.00	782.00	805.00
Finance Cost	1564.09	1380.08	1196.07	1012.06	828.05	644.04	460.03	276.02	92.01	0.00	0.00
Capital Repayments	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	1727.80	0.00	0.00
CDM Benefit	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18
Total Costs	**3261.71**	**3100.70**	**2939.69**	**2778.68**	**2617.67**	**2456.66**	**2295.65**	**2134.64**	**1973.63**	**176.82**	**199.82**

Year	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055
Energy (GWh)	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00	409.00
O&M Cost	828.00	851.00	874.00	897.00	920.00	943.00	966.00	989.00	1012.00	1035.00	1058.00
Finance Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Capital Repayments	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDM Benefits	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18	605.18
Total Costs	**222.82**	**245.82**	**268.82**	**291.82**	**314.82**	**337.82**	**360.82**	**383.82**	**406.82**	**429.82**	**452.82**
Year	**2056**	**2057**	**2058**	**2059**	**2060**	**2061**					
Energy (GWh)	409.00	409.00	409.00	409.00	409.00	409.00					
O&M Cost	1081.00	1104.00	1127.00	1150.00	1173.00	1196.00					
Finance Cost	0.00	0.00	0.00	0.00	0.00	0.00					
Capital Repayments	0.00	0.00	0.00	0.00	0.00	0.00					
CDM Benefits	605.18	605.18	605.18	605.18	605.18	605.18					
Total Costs	**475.82**	**498.82**	**521.82**	**544.82**	**567.82**	**590.82**					

APPENDIX – I: Energy and Cash Outflow of Caledonia Reservoir Project (costs & benefits are given in million LKR)

Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Energy (GWh)	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00
O&M Cost	98.44	131.25	164.07	196.88	229.69	262.51	295.32	328.13	360.95	393.76	426.57
Finance Cost	0.00	11948.33	11543.30	11138.28	10733.25	10328.22	9923.19	9518.16	9113.14	8708.11	8303.08
Capital Repayments	0.00	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08
CDM Benefits	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68
Total Costs	**-855.24**	**14928.99**	**14556.77**	**14184.56**	**13812.34**	**13440.13**	**13067.91**	**12695.70**	**12323.48**	**11951.27**	**11579.05**
Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**
Energy (GWh)	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00
O&M Cost	459.39	492.20	525.01	557.83	590.64	623.45	656.27	689.08	721.89	754.71	787.52
Finance Cost	7898.05	7493.02	7087.99	6682.97	6277.94	5872.91	5467.88	5062.85	4657.82	4252.80	3847.77
Capital Repayments	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08
CDM Benefits	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68
Total Costs	**11206.84**	**10834.62**	**10462.41**	**10090.19**	**9717.98**	**9345.76**	**8973.55**	**8601.34**	**8229.12**	**7856.91**	**7484.69**
Year	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**
Energy (GWh)	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00
O&M Cost	820.33	853.15	885.96	918.77	951.59	984.40	1017.21	1050.03	1082.84	1115.65	1148.47
Finance Cost	3442.74	3037.71	2632.68	2227.66	1822.63	1417.60	1012.57	607.54	202.51	0.00	0.00
Capital Repayments	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	3803.08	0.00	0.00
CDM Benefits	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68
Total Costs	**7112.48**	**6740.26**	**6368.05**	**5995.83**	**5623.62**	**5251.40**	**4879.19**	**4506.97**	**4134.76**	**161.97**	**194.79**

Year	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**2055**
Energy (GWh)	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00	664.00
O&M Cost	1181.28	1214.09	1246.91	1279.72	1312.53	1345.35	1378.16	1410.97	1443.79	1476.60	1509.41
Finance Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Capital Repayments	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDM Benefits	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68	953.68
Total Costs	**227.60**	**260.41**	**293.23**	**326.04**	**358.85**	**391.67**	**424.48**	**457.29**	**490.11**	**522.92**	**555.73**
Year	**2056**	**2057**	**2058**	**2059**	**2060**	**2061**					
Energy (GWh)	664.00	664.00	664.00	664.00	664.00	664.00					
O&M Cost	1542.23	1575.04	1607.85	1640.67	1673.48	1706.29					
Finance Cost	0.00	0.00	0.00	0.00	0.00	0.00					
Capital Repayments	0.00	0.00	0.00	0.00	0.00	0.00					
CDM Benefits	953.68	953.68	953.68	953.68	953.68	953.68					
Total Costs	**588.55**	**621.36**	**654.17**	**686.99**	**719.80**	**752.61**					

APPENDIX – J: Variable Unit Cost of Thermal Power Plants

June 2017

Variable Unit Cost Based on Station Specification at Based Load Running	
Power Station	**Unit Cost (LKR/kWh)**
LAKVIJAYA UNIT 01	6.83
LAKVIJAYA UNIT 02	6.85
LAKVIJAYA UNIT 03	7.04
SAPU B1 HF	17.80
SAPU B2 HF	17.80
BARGE	17.86
SAPU A HF	19.42
KCCP – NAPTHA	19.58
KCCP – DIESEL	19.69
WEST COAST	19.91
UTHURU JANANI	19.96
AES	20.21
ACE – MATARA	21.22
ACE – EMBILIPITIYA	21.65
ASIA POWER	21.80
EMERGENCY 60	23.96
KPS(GT7)	32.34
KPS(GTT)	51.17

Source: System Control Centre

APPENDIX – K: Daily Recorded Maximum Night Peak Operation of Upper Kotmale Hydropower Plant (Source: System Control Centre)

Values are given in MW

2014												
Day	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	140	150	149	40	146	150	150	150	150	75	152	33
2	100	150	150	40	59	135	150	152	150	75	150	150
3	120	75	98	0	114	150	140	152	150	75	150	150
4	150	150	100	0	150	80	150	152	150	75	150	145
5	150	100	40	60	40	75	150	152	75	75	150	120
6	120	150	80	130	75	65	150	150	150	75	150	150
7	120	150	40	40	100	100	120	150	80	75	150	150
8	150	60	60	0	85	150	150	150	110	75	150	150
9	120	120	150	75	68	152	100	150	120	75	150	150
10	150	120	120	40	150	75	145	150	135	75	150	150
11	140	120	140	120	150	117	150	152	120	150	150	150
12	146	120	75	120	0	152	150	84	135	150	150	150
13	150	120	40	120	40	152	150	150	100	120	150	150
14	150	75	60	75	150	128	150	120	150	150	150	150
15	150	150	150	80	60	150	150	100	75	150	150	150
16	75	150	80	0	100	150	150	150	75	150	150	142
17	120	150	120	40	60	150	140	150	75	115	150	150
18	152	114	110	150	150	150	150	60	75	80	150	150
19	150	75	135	150	148	150	150	150	75	150	150	150
20	150	40	75	150	100	150	150	150	75	150	135	150
21	152	75	118	0	60	150	120	150	75	150	150	150
22	120	100	150	40	40	150	100	150	40	150	120	152
23	150	140	60	96	40	75	110	150	75	150	150	152
24	134	120	75	0	100	150	100	150	75	150	100	150
25	100	85	40	0	100	119	130	135	76	150	150	150
26	150	120	40	120	44	135	130	135	76	150	150	150
27	150	100	40	60	40	150	150	150	76	150	150	152
28	115	150	75	0	0	150	150	120	150	150	152	150
29	150		75	100	80	150	120	150	130	150	150	152
30	150		75	66	50	135	120	150	76	150	150	152
31	150		75		0		150	150		150		150

2015												
Day	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	150	150	0	100	120	120	150	120	150	150	76	150
2	150	150	0	150	152	150	90	150	100	150	152	150
3	150	150	0	150	120	100	150	100	80	120	152	150
4	150	150	0	110	150	150	100	100	150	150	152	150
5	150	145	0	130	150	150	150	120	150	76	152	150
6	130	150	0	135	150	152	150	80	130	150	152	150
7	120	150	0	150	150	150	100	60	150	150	152	120
8	130	150	0	152	152	115	75	150	140	150	152	150
9	100	135	0	150	150	120	100	150	150	150	152	150
10	150	150	0	150	150	120	120	80	120	150	152	150
11	150	150	75	150	150	80	150	150	100	100	152	80
12	150	150	51	100	120	75	140	150	150	150	150	150
13	150	150	75	150	150	100	120	98	150	150	150	140
14	150	152	75	150	150	120	120	150	40	150	152	150
15	150	152	75	150	150	110	150	152	120	152	152	150
16	150	152	75	150	150	150	150	150	120	120	150	150
17	150	135	75	150	150	150	150	142	150	150	152	150
18	152	130	75	150	100	150	150	120	150	150	150	150
19	150	120	76	150	150	150	150	120	143	150	152	150
20	150	150	50	120	150	150	140	150	150	152	150	150
21	150	75	100	150	150	150	150	100	135	152	150	150
22	150	75	140	150	140	120	150	142	98	150	150	150
23	150	75	150	75	150	60	75	150	150	150	150	150
24	150	75	120	75	60	120	150	80	150	150	150	150
25	150	75	125	75	150	150	150	150	152	150	150	150
26	80	0	80	150	150	75	150	100	150	120	150	150
27	80	0	140	120	120	75	75	150	150	152	150	150
28	80	0	75	150	75	150	150	46	150	152	150	150
29	150		75	100	80	150	100	120	152	152	150	150
30	150		150	150	75	150	120	150	150	152	150	150
31	150		150		120		150	135		76		140

2016												
Day	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	150	120	75	60	75	150	150	75	100	40	150	80
2	150	115	40	75	80	150	150	100	120	150	40	40
3	150	120	40	75	40	150	150	40	120	40	80	130
4	150	40	54	50	75	150	0	120	140	40	100	0
5	144	140	75	70	40	150	150	100	40	40	120	150
6	150	75	60	40	50	150	150	150	40	40	150	75
7	135	140	40	70	80	112	75	150	40	40	100	80
8	140	150	75	40	75	150	80	75	40	75	114	100
9	150	40	75	35	80	120	140	110	60	80	100	0
10	150	150	75	80	0	100	150	53	150	40	100	130
11	114	120	40	150	80	150	120	115	120	120	120	0
12	95	130	75	100	75	130	150	40	75	75	116	75
13	128	150	0	120	120	150	150	75	14	0	130	40
14	140	150	40	80	150	150	120	150	120	70	75	120
15	150	75	60	120	152	140	150	150	40	100	100	75
16	150	115	75	120	152	150	150	90	80	150	60	100
17	150	80	40	100	150	150	150	150	70	150	80	50
18	150	120	75	92	150	150	150	75	40	65	100	75
19	150	100	75	60	150	75	60	40	75	0	150	150
20	150	75	40	150	150	150	150	140	120	75	120	90
21	132	80	75	0	150	150	75	60	40	70	120	95
22	150	150	75	40	150	100	75	80	120	100	120	0
23	150	150	105	80	150	150	150	150	75	120	115	110
24	150	58	60	120	115	150	130	80	150	150	140	120
25	140	0	60	40	150	150	120	75	120	150	137	0
26	140	75	40	75	140	60	115	100	60	120	150	90
27	150	75	75	40	150	40	130	150	150	100	150	40
28	100	75	50	40	150	140	150	141	80	150	50	40
29	120	40	75	71	150	150	130	140	120	80	120	100
30	120		75	75	150	40	150	75	150	75	0	40
31	150		40		150		150	80		75		75

2017									
Day	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
1	110	75	52	40	128	150	150	40	50
2	80	80	52	116	100	140	0	80	150
3	60	0	0	58	100	131	0	40	150
4	40	62	52	42	75	116	0	150	110
5	75	0	0	0	0	150	40	150	150
6	120	75	0	0	0	150	75	150	60
7	0	40	75	40	0	100	75	150	150
8	40	66	60	45	40	120	120	120	150
9	60	54	51	140	0	150	150	115	150
10	75	0	43	64	75	150	0	60	150
11	150	45	40	40	40	150	140	114	130
12	75	40	75	75	40	75	40	65	128
13	75	51	75	80	75	150	100	75	140
14	115	60	75	140	60	75	40	109	150
15	150	60	75	130	86	75	75	150	150
16	0	0	60	0	75	75	100	120	150
17	40	38	75	0	40	75	40	60	150
18	0	76	60	75	75	150	80	120	120
19	60	40	75	40	40	40	40	150	80
20	0	41	0	0	0	120	80	150	130
21	0	40	0	0	60	120	150	100	140
22	0	0	0	50	0	150	60	150	130
23	75	0	47	120	75	60	120	150	100
24	40	0	45	60	108	75	60	80	90
25	135	0	40	40	140	150	115	50	80
26	0	75	65	75	150	0	0	150	80
27	0	40	50	75	150	120	40	150	150
28	130	40	55	0	150	60	115	120	80
29	0		39	70	75	40	150	100	80
30	0		60	0	150	150	40	103	150
31	90		0		150		40	150	