Energy Investment and Emissions Planning for Electricity Generation in Myanmar

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Abstract

Hydropower plays a critical role in supplying electricity generation in the developing nation of Myanmar. Over the next 15 years (2015 – 2030) with anticipated rapid social and economic development in Myanmar, the demand for electricity is expected to increase from 23718 GWh in 2015 to 136605 GWh in 2030, which is nearly a six-fold increase. The aim of this thesis is to investigate the critical role of hydropower in the Myanmar electricity sector in meeting projected demand in 2030. As a result this thesis presents a detailed analysis of electricity generation in Myanmar using chiefly two methods: Energy Return on Investment (EROI) and Carbon Emissions Pinch Analysis (CEPA).

The contributions of this thesis to literature and Myanmar include: (1) the development of a low energy investment, low emissions roadmap towards achieving electricity demand in 2030 for Myanmar; (2) the identification of 20 storage-type hydropower stations that with excellent EROI values and low energy payback times, which help form the foundation of the future development roadmap; and (3), the determination of dam-type-specific empirical correlations for EROI by inputting the estimated electricity output (based on head, water flow, overall efficiency and capacity factor) and dam volume.

By implementing the recommendation of a further 20 hydropower plants, beyond the currently installed and under-construction plants, Myanmar can achieve its ambitious 2030 electricity supply target, 136605 GWh, in which a major of generation comes from hydropower (69%). The remaining generation comes from natural gas (24%), coal 3340 GWh (2.5%) and other renewables such as solar, wind and biomass (4.5%). Compared to the Myanmar's current National Electricity Master Plan (2014-2030) adopted by Ministry of Electric Power, the recommendations in this thesis can lead to 41% mitigation of carbon emissions with 7% less energy investment.

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Nomenclature

Roman

a	Region Coefficient
A	catchment area, (km^2), area of powerhouse (m^2)
B	width of the open channel (m), river bed width (m)
C_p	hydropower coefficient
d	height of powerhouse, (m)
D	inner diameter of waterway (m)
D_m	inner diameter of penstock (m)
DSL	Dead Storage Level (m)
ED_{in}	direct energy input
ED_{out}	direct energy output
FRL	Full Reservoir Level (m)
g	free fall acceleration (m/s^2)
h_a	available drawdown (m)
H	height of the open channel (m), hydraulic head, head (m)
H_d	dam height (m)
H_e	effective head (m), head, H (m)
I_k	energy per unit of the given co-efficient
L	dam crest length (m), total length of waterway (m)
m	upstream slope of dam
MDDL	Minimum Drawdown Level (m)
MWL	Maximum Water Level (m)
n	number of waterway, number of tunnel, number of power house, downstream slope of dam
O_j	energy per unit of the given output coefficient
P	Power output (kW)
PV	photovoltaic
q	specific discharge ($m^3/s/km^2$)
Q	flow or power discharge (m^3/s), maximum unit discharge (m^3/s)
Q_{plant}	maximum plant discharge (m^3/s)
Q_{Ann}	maximum plant discharge of Ann project (m^3/s)
Q_{max}	maximum unit discharge (m^3/s)
Q_f	design flood discharge (m^3/s)

R	tunnel radius (m)
t	thickness of backfill concrete (cm)
t_m	thickness of steel conduit (mm)
t_o	lining concrete thickness (m)
V_c	dam construction volume (m^3), Concrete volume (m^3)
$V_{c\text{-}plant}$	concrete volume used at the specific power plant (m^3)
$V_{c\ Ann}$	concrete volume of Ann project (m^3)
V_e	dam excavation volume (m^3)
V_f	dam embankment volume (m^3)
vj	a set of well-defined coefficient output
W	dam crest width (m)
W_g	weight of gate (ton)
W_p	weight of steel conduit (ton)
W_r	weight of reinforcement bars (ton)
W_s	weight of screen (ton)
V°	volumetric flow rate at each turbine (m^3/s)

Greek

γ_k	input co-efficient
ρ	water density (kg/m^3)
η	combined efεency of turbine and generator

Abbreviations

CCT	Clean Coal Technology
CEPA	Carbon Emissions Pinch Analysis
CFRD	Concrete Faced Rock-fill Dam
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide Equivalent
CVC	Conventional Vibrated Concrete
EF	Emission Factor
EROI	Energy Return on Investment
$EROI_{stnd}$	Standard Energy Return on Investment
$EROI_{soc}$	societal EROI
$EROI_{mm}$	EROI at mine-mouth

$EROI_{pou}$	EROI at point of use
$EROI_{ext}$	extended EROI
EPT	Energy Payback Time
GEF	Grid Emissions Factor
GHG	Green House Gas
HRT	head race tunnel
HEFD	Homogeneous Earth-Fill Dam
LCA	Life Cycle Assessment
N_2O	Nitrous Oxide
OMC	Optimum Moisture Content
RCC	Roller Compacted Concrete
RPS	Renewable Portfolio Standard
USC	Ultra Supercritical Plant
ZTRFD	Zone Type Rock-Fill Dam
ZTEFD	Zone Type Earth-Fill Dam

Chapter 1
Introduction

1.1 Context

Developing countries like Myanmar are under pressure to increase electricity production to sustain economic development and growth, while also minimising the growth in carbon emissions. To succeed in this dual challenge the natural renewable energy resources of the country need to be fully utilised where possible. For Myanmar, a country richly blessed with rainfall, rivers and mountains, there is enormous potential for more low carbon hydropower. However, to make the bold decision to have more hydro dams in Myanmar there is a need to first understand the energy return value of existing hydro dams and future dams, and secondly to understand the relative contributions that each type of power generation is having on electricity carbon emissions in Myanmar.

To undertake this study Energy Return on Investment (EROI) has been identified as a useful parameter for understanding the quality of an energy resource and the conversion efficiency of an energy production technology. Formally EROI is the amount of energy that has to be invested so as to produce a certain amount of energy in an energy production process. EROI has been the focus of many energy supply studies since the 1980s and for energy sector studies it is important to determine whether an energy resource provides a net gain to the economy or not (Murphy & Hall, 2010). More recently, the use of EROI principles has been combined with Carbon Emissions Pinch Analysis (CEPA) to examine energy supply and demand related issues.

CEPA is a useful methodology that is based on pinch analysis techniques used in heat and mass integration for minimising energy and water usage. The CEPA method is ideal for analysing macro-scale energy sector planning situations where emissions reduction is important (Walmsley et al., 2014). The combination of EROI and CEPA enables the possible renewable energy mixes of a country to be evaluated in terms of emissions targets and acceptable economics as predicted by net energy returns to society.

In California and New Zealand, where the electricity sectors are seeking to reduce carbon emissions by reaching designated renewable electricity targets, CEPA and EROI analysis have been applied (Walmsley et al., 2014).Options for carbon emission reduction have been evaluated and the extra energy that will need to be expended by the economy to make that possible has been determined.

Regarding EROI analysis, many studies have focused on liquid fuels and the energy return of gasoline from oil, ethanol from biomass, diesel from biomass, and corn-based ethanol (Hall et al., 2014). Other studies have focused on the EROI of converting traditional renewable resources such as hydropower, wind power and geothermal into electricity. Hall et al. (2014) reported that hydropower generation systems achieve the highest EROI values. Fernando (2010) evaluated the Aratiatia power station with an installed capacity of 90 MW in New Zealand, which delivered an EROI of approximately 50. Weiβbach et al., (2013) observed the small hydropower plant, which is <1 MW, has a lower EROI value and a large hydropower plant, >1 MW, has a higher EROI value, even larger than 100.

Most of these hydro studies have focused on EROI results of hydropower plants without necessarily following the same methodology and system boundaries. As a result, the literature EROI results, in many cases, cannot be reliably compared. Atlason and Unnthorsson (2014) followed the methodology and system boundaries formulated by Murphy et al., (2011) and analysed a storage type hydropower plant with 690 MW installed capacity in Iceland. Three different EROI values were reported in their study (110.2, 112.7, and 340.7) for three different boundary conditions of energy outputs and inputs.

Literature EROI values can be compared with other EROI values as long as they follow the same methodology and system boundaries. The lack of EROI values for hydropower plants using a common analysis approach represents a gap in the literature. Without sufficient EROI analysis across multiple dam types and capacities, it is difficult to accurately estimate EROI values for future hydropower projects. Developing a standardised approach for predicting EROI values for future hydropower resources will be insightful for energy policy making in energy sector.

1.2 Thesis Aim

The aim of this thesis is to investigate the critical role of hydropower in the Myanmar electricity sector in meeting projected demand in 2030, while also minimising grid emissions, using EROI and CEPA analysis. The scope of the EROI analysis includes constructed, under-construction and planned storage type hydropower plants in Myanmar. The scope of the CEPA analysis includes the entire Myanmar electricity sector as it currently stands and its various compositions in 2030. To achieve the aim, $EROI_{stnd}$ values and Energy Payback Times (EPT) (Atlason and Unnthorsson, 2014) for 18 constructed, 5 under-construction and 24 planned storage type hydropower plants in Myanmar are determined. By using $EROI_{stnd}$ values, linear regression models are formulated to correlate key factors that determine $EROI_{stnd}$ values in future hydropower sector. These linear models are then applied to predict $EROI_{stnd}$ values for future planned storage type hydropower plants in Myanmar. Using hydropower as a source of low carbon emission energy generation, the selection of the best option of electricity generation mix to reduce carbon emissions for the Myanmar electricity sector by year 2030 is investigated based on CEPA techniques.

1.3 Thesis Structure

A literature review will first be presented in Chapter 2 on the theory and methods of CEPA, methodology and system boundaries for determining EROI, review on EROI values of fuels especially hydroelectric power generation and a general overview of reservoir dams and appurtenant structures are described.

Chapter 3 gives a detailed account of Myanmar hydropower resources especially storage type hydropower plants in terms of current and future generation. Data are provided by Ministry of Electric Power (MOEP), Myanmar.

Chapter 4 provides Myanmar energy and electricity sector outlook and the analysis of the electricity sector using Carbon Emissions Pinch Analysis (CEPA) to decide the best possible option of electricity generation mix target. The generation target options are based on the "National Electricity Master Plan" (2014-2030) proposed by Japan International Cooperation Agency (JICA).

In Chapter 5, the methodology and system boundaries for EROI calculations formulated by Murphy et al., (2011) are applied coupled with the predictive equations from Kansai Electric Power Co. Inc., Japan for energy input calculations. The chapter also presents the underlying assumptions of the EROI analysis, followed by reporting and discussing the resulting $EROI_{stnd}$ values for storage type hydropower plants in Myanmar.

In Chapter 6, the linear regression equations resulted from the analysis of the correlation between the $EROI_{stnd}$ values and the ratio of energy costs and production for different dam types are presented. In addition, the energy expended analysis on the future electricity generation options for Myanmar will also be discussed by recommending the best-fitted $EROI_{stnd}$ values for 20 planned hydropower projects.

The main conclusions and recommendations for further works are presented in Chapter 7 as a final chapter of this thesis.

Chapter 2
Literature Review

2.1 Introduction

Myanmar is well endowed with energy resources and both renewable and non-renewable energy resources are available for electricity generation, especially hydropower, coal and natural gas (Myanmar National Energy Management Committee, 2014). Myanmar has a high proportion of renewable generation mainly due to the large amount of hydropower generation (68% in 2015) (Ministry of Electric Power, 2015). However, its hydropower generation capability is the lowest amongst five neighboring countries, China, India, Bangladesh, Laos and Thailand. It accounted for 5.8 % in 2013 although technically exploitable capability is 240.20 TWh/y, which is the third largest potential after India and China, 660 TWh/y and 2474 TWh/y (Khaing, 2015a).

According to "The National Electricity Master Plan" (2014-2030) which will be implemented by MOEP in cooperation with Japan International Cooperation Agency (JICA), New Japan Engineering Consultants Inc. (NEWJC Inc.) and Kansai Electric Power Co., Inc., it is generally expected that a high renewable target for electricity generation in 2030 is a realistic approach and achievable aspiration for Myanmar (Japan International Cooperation Agency et al., 2014). However, the best renewable energy sites should be evaluated, not only from the generation mix target view but also from the perceptive of environmental footprint, social impact and other political views. In addition to this, the impacts of electricity generation through carbon, water and land footprints also play vitally important roles in deciding the best hydropower generation sites (Lovins, 2011).

Carbon Emissions Pinch Analysis (CEPA) developed by Tan, Foo and co-workers (Tan & Foo, 2007) is a useful technique to evaluate the impact of electricity generation by means of carbon footprint for renewable and non-renewable energy mix. Nevertheless, CEPA techniques alone cannot provide the insights into the best possible renewable energy mix target of a country. Energy Return on Investment (EROI) principles are also needed to evaluate whether the generation mix is economically relevant (Walmsley et al., 2014), and viability of net energy return for Myanmar's society established. The concept of EROI was developed 40 years ago by American systems ecologist Charles Hall and it is a useful technique to predict the energy efficiency for both fossil fuel and non- fossil fuel (Walmsley et al., 2014). In this chapter, a literature review on theory and methods of CEPA, definitions of EROI, methodology and system boundaries for determining EROI, EROI values of various fuels and the essential features of storage type hydropower plants (as the energy input of EROI calculation) are presented.

2.2 Theory and Methods of Carbon Emissions Pinch Analysis

"Carbon Emissions Pinch Analysis (CEPA) is based on the application of traditional Pinch Analysis techniques used in heat and mass integration to minimize energy and water usage" (Walmsley et al., 2014, p. 657). Although the techniques were initially focused on industrial sites, they can be extended to utilize the broader macro-scale applications such as electricity generation sector and transport sector (Walmsley et al., 2014). CEPA techniques can be applied to studying the emissions constraints planning, including Carbon Capture and Storage (CCS), multi-period scenarios and CO_2 sources and sinks (Tan et al., 2013; Lee et al., 2014).

A major component of CEPA is the construction of multiple supply and demand composite curves. An example of the electricity generation and carbon emissions method is illustrated in Table 2.1 and Figure 2.1. According to this example, the multiple fuel sources for electricity generation providing the needed supply are plotted on the x-axis and total equivalent carbon emissions (kt CO_2-e) from these supply sources and demand are plotted on the y-axis. The Emission Factor (EF) is calculated in terms of the amount of emissions produced divided by unit of electricity, for instance kt CO_2-e/GWh. The fuel source with the lowest Emissions Factor (EF) is plotted first, and then the second highest, then the third highest is plotted and so on. In this context, Emission Factor (EF) is equal to the slope of the supply profile. It is seen that the overall Grid Emissions Factor (GEF) is equal to total emissions factor of the system (Tan & Foo, 2007; Atkins et al., 2010).

Table 2.1 Electricity generation and carbon emissions example Table (Walmsley et al., 2014).

	Quantity (GWh)	Emissions (kt CO_2-e)	Emissions Factor (kt CO_2-e/GWh)
Demand			
Industrial	350	350	1.00
Residential & Commercial	650	650	1.00
Total Demand	1000	1000	1.00
Supply			
Renewables	300	0	0
Fuel A	400	200	0.50
Fuel B	300	800	2.67
Total Supply	**1000**	**1000**	**1.00**

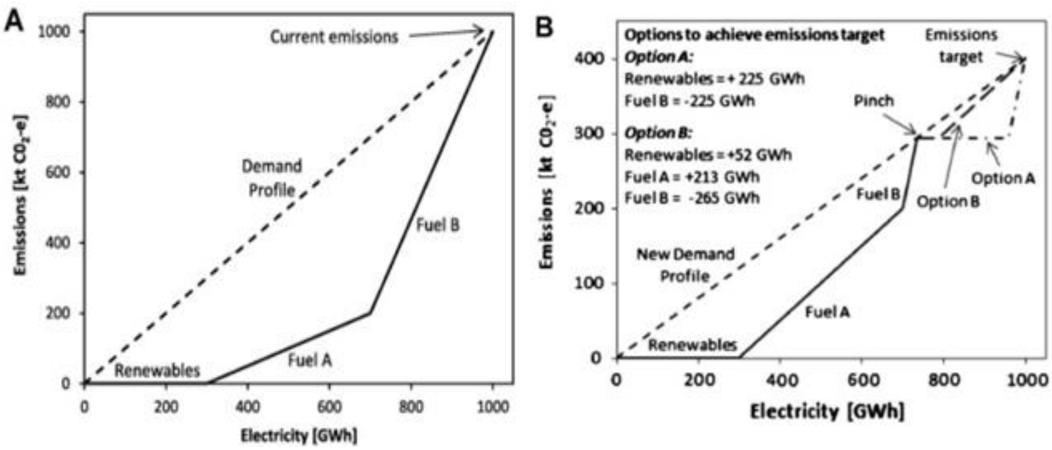


Figure 2.1 Demand and supply composite curves example for before (A) and after carbon emissions reduction (B) for electricity generation (Walmsley et al., 2014).

Figure 2.1 A describes the current supply and demand for electricity generation and its carbon emissions 1000 kt CO_2-e. If the new carbon emissions' target requires decreasing to 400 kt CO_2-e which is illustrated in Figure 2.1B, the demand is now touched to the supply by pinching the two points at a pinch point target due to the fuel switching in options A and B. The emissions' objective has been achieved by switching fuel A and fuel B to the needed renewable resources. There are many composition targets that can attain the objective; however, options A and B are crucial limits binding the diverse combinations. In Figure 2.1B, carbon emissions are lowered to 400 kt CO_2-e in option A in terms of switching from the 225 GWh of fuel B to renewables. Likewise, the needed emissions target is achieved in option B in terms of switching from the 265 GWh of fuel B to 213 GWh of fuel A and 52 GWh of renewables respectively (Tan & Foo, 2007; Atkins, 2010).

By applying the concept of CEPA techniques, Walmsley, et al., (2015a) analyzed California's Renewable Portfolio Standard (RPS) which needs 33 % of all retail electricity sales to be generated by renewable energy sources by 2020 without greater hydropower electricity generation. CEPA methodology was utilized to reduce emissions in the electricity sector and to examine the positive outlook that is the average emissions factor of imported electricity to California, which can be reduced from 0.379 kt CO_2-e/GWh to a minimum of 0.290 kt CO_2-e/GWh by replacing natural gas for coal (Walmsley et al., 2015). In addition, Walmsley et al., (2014) investigated the New Zealand electricity sector in order to maintain a renewable electricity target above 90 % up to 2050, while increasing the annual generation rate 1.5 %, also allowing for a 50% switching to plug-in vehicles for personal uses. The authors attributed the two cases of reducing overall emissions from the New Zealand electricity sector to 1990 levels (3730 kt CO_2-e) and 2011 levels (5580 kt CO_2-e) by 2050, to a strong political will of the New Zealand government. As part of this thesis, a Carbon Emission Pinch Analysis (CEPA) technique has been adopted and the emissions reduction status of Myanmar regarding "The National Electricity Master Plan" (2014-2030) is evaluated, and detailed discussions and results are presented in Chapter 4.

2.3 Explicit Definitions of Energy Return on Investment (EROI)

Energy Return on Investment (EROI) is simply defined as the ratio of energy gained from a particular energy process to the energy required to be used - (directly and indirectly) - in that process. EROI can be defined as follows:

$$\text{EROI} = \frac{\text{Energy gained}}{\text{Energy required to get that energy}} \tag{2-1}$$

(Murphy & Hall, 2010)

Energy gained can be defined as the form of a primary energy source for instance, natural gas, crude oil or coal, or as the form of a refined energy carrier for example, electricity, gasoline or briquettes (Murphy & Hall, 2010). In this regard, energy is defined as the physical ability to do useful work, which is done when a body is moved by a force. The physical ability to do work is represented by the enthalpy of the fuel. Therefore, the numerator and denominator of EROI is measured in heat units such as Btu or kJ and the ratio will be derived as dimensionless e.g 30, which describes a particular process which yields 30 kJ on an investment of 1 kJ (Murphy & Hall, 2010; EJOLT, n.d).

EROI is also known as the assessment of energy surplus, energy balance, or net energy analysis and preferred to be used as Energy Return on Energy Investment (EROEI or ERoEI) by some practitioners. The EROI methodology uses the first law of thermodynamic analysis, and energy quality differences such as heat, work and electricity are not counted in the analysis (Hall et al., 1986; Murphy & Hall, 2010).

2.4 Methodology and System Boundaries for Determining EROI

The original concept of EROI is the ratio between energy delivered against the energy required in the process, and can be described as follows (Hall, 2011):

$$\text{EROI} = \frac{\text{Quantity of energy supplied}}{\text{Quantity of energy used in supply process}} \quad (2\text{-}2)$$

This equation seems to be straightforward at first, but it becomes more and more complex when one decides what should be included in the energy supplied and quantity of energy used in the supply process. For instance: Is the energy required to transport all the material and equipment to a specific location included? Is the energy that was used to create that material and equipment included? What other energy is needed to create the machines which were used to create the material and equipment? And so on. Therefore, various factors can be considered within an EROI equation, but no standard exists on what should be included in the numerator and denominator or where the boundaries should be set for energy supplied and energy used in supply process (Atlason & Unnthorsson, 2013).

It is claimed that no consistent framework exists around the concept of EROI in the abovementioned equation; it can be manipulated to give the desired results. Mulder & Hagens (2008) recommend that there should be a consistent framework; therefore, they proposed the following equation:

$$\text{EROI} = \frac{\text{ED}_{\text{out}}}{\text{ED}_{\text{in}} + \sum \gamma_k \text{I}_k} \quad (2\text{-}3)$$

where ED_{out} is defined as the direct energy output, ED_{in} is defined as the direct energy input, γ_k is input co-efficient and I_k is the energy per unit of the given co-efficient for an energy process. This equation does not consider some parameters for example, indirect energy outputs, non-energy outputs, and so on. In some cases, the parameters might be difficult to convert to the energy equivalents, however, co-products do have energy content for instance, co-products from farming to produce oil seeds, or hot water from a geothermal plant, various grades of fuels such as lubricants produced from oil refinery, therefore they should be accounted for (Murphy et al., 2011; Atlason & Unnthorsson, 2013).

Mulder and Hagens (2008) provided another EROI equation which is:

$$\mathrm{EROI} = \frac{\mathrm{ED_{out}} + \sum \mathrm{V_j O_j}}{\mathrm{ER_{in}} + \sum \gamma_k \mathrm{I_k}} \quad (2\text{-}4)$$

where ED_{out} is defined as the direct energy output, v_j is defined as a set of well-defined coefficient output, O_j is the energy per unit of the given output coefficient in terms of the numerator of EROI equations. For denominator, ED_{in} is defined as the direct energy input, γ_k is defined as a set of well-defined input co-efficient and I_k is defined as the energy per unit of the given coefficient. However, some factors such as soil erosion, ground water pollution and loss of food production are needed to be considered within these equations, and there is no relevant set of boundaries for energy outputs and inputs (Atlason & Unnthorsson, 2013).

Mulder and Hagens (2008) found that three different EROI estimations existed for corn ethanol although it had been stated in literature using the same boundaries at energy inputs and outputs. In order to assist this case, the authors proposed the appropriate approach of different EROI calculation by using different inputs in terms of first order, second order and third order. In the case of first order, only direct energy inputs and outputs are included. For second order EROI involves energy and non-energy indirect inputs and co-product outputs; for third order, it is needed to consider externalities of the energy production process such as water usage in the corn ethanol process (Mulder & Hagens, 2008).

However, they do not provide any clarification on the standardization related to the boundaries of EROI (Atlason & Unnthorsson, 2013). “They merely mention that boundaries should be drawn and well defined, except on the 2nd level EROI where they mention that boundaries can be drawn where the energy input is less than 1 % of the energy invested” (Atlason & Unnthorsson, 2013, pg. 274).

Hall et al., (2009) agree with the conceptualization of Mulder and Hagens (2008) as “a need for a better way to think about EROI” and believe that EROI boundaries should ensure the consistency of various fuels analysis approach. To aid in that effort, they developed a number of additional sub definitions of EROI. They reviewed societal EROI called $EROI_{soc}$. This is derived for all of a nation or society’s fuels collectively by adding all gains from fuels and all costs of obtaining them, and is calculated as follows (Hall et al., 2009):

$$\text{EROI} = \frac{\text{Summation of the energy contents of all fuel delivered}}{\text{Summation of all the energy costs of getting those fuels}} \quad (2\text{-}5)$$

Hall et al., (2009) also proposed new concept of EROI at mine-mouth (or well-head, farm gate, etc.), which is the most common use of EROI namely $EROI_{mm}$. In addition, a similar concept of $EROI_{mm}$ is proposed, which is EROI at "point of use" namely $EROI_{pou}$, which involves the energy to find, produce, refine, and transport to point of use. This ratio is calculated as follows:

$$\text{EROI}_{\text{pou}} = \frac{\text{Energy returned to society}}{\text{Energy required to get and delivered that energy}} \quad (2\text{-}6)$$

They define the $EROI_{ext}$ as "extended EROI" which can evaluate not only the delivered energy but also the consumed energy, such as the energy used at the bridges, highways, etc. for transport of fuels and defined as follows:

$$\text{EROI}_{\text{ext}} = \frac{\text{Energy returned to society}}{\text{Energy required to get, deliver and use that energy}} \quad (2\text{-}7)$$

The above three equations can be apparently used in the first, second and third order of EROI formulated by Mulder and Hagens (2008), however, it could require someone with inspiration to formulate the combination of these two approaches, and to assist a more precise and comprehensive EROI (Hall et al., 2009).

In 2011, Murphy et al., successfully proposed a formal methodology, system boundaries and nomenclature of EROI analysis which offers a much greater degree of consistency and flexibility of boundaries, thus all EROI numbers across various processes can be specifically compared. It is aimed at providing a clear and concise conceptual framework to select the appropriate boundaries for the standard EROI analysis as well as other energy ratios.

According to the proposed methodology, selecting the system boundaries for EROI calculation is somewhat similar to the Life Cycle Assessment (LCA) analytical technique in which a boundary has been chosen and all inputs beyond that boundary are excluded from analysis. In this regard, as the numerator of EROI ratio, energy outputs can be selected by using three system boundaries as in Figure 2.2. The energy outputs can be counted as system boundary 1 which includes extraction (mine – mouth), as system boundary 2 which includes extraction process to intermediate process (refinery gate), and as system boundary 3 which consists of an extraction process up to distribution (final demand). The system boundary can vary due to a greater variety of direct and indirect energy (Murphy et al., 2011).

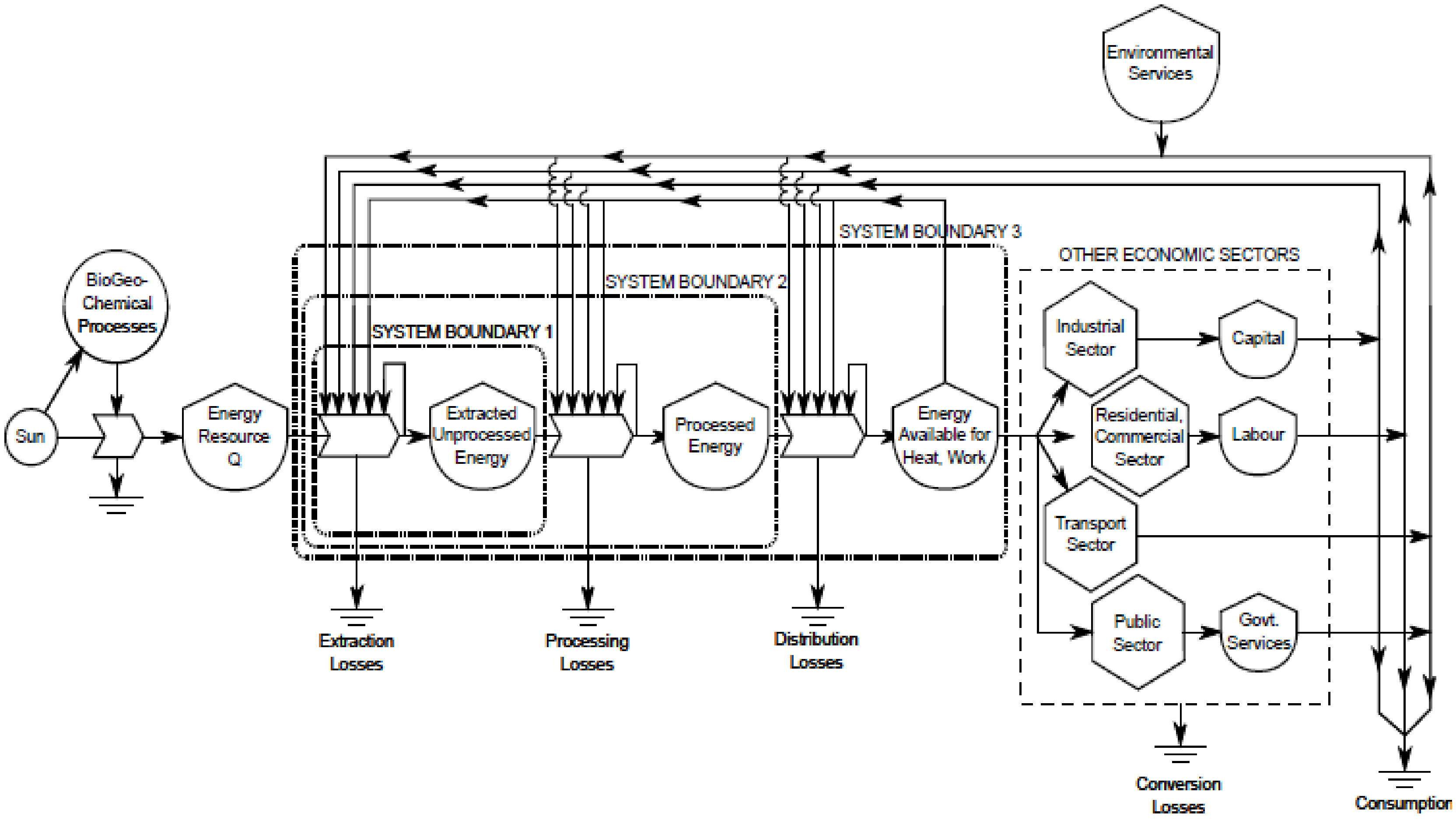


Figure 2.2 System boundaries selection based on the idea of Hall et al., (Murphy et al., 2011).

The material inputs that determine the denominator of the EROI ratio for energy inputs can be counted by using the different levels energy production processes as illustrated in Figure 2.3. Level 1 includes internal energy consumption; level 2 includes energy inputs from the rest of the energy sector; level 3 includes embedded energy inputs of materials, and levels 4 and 5 include embodied energy in supporting labour and other auxiliary economic services respectively (Murphy et al., 2011).

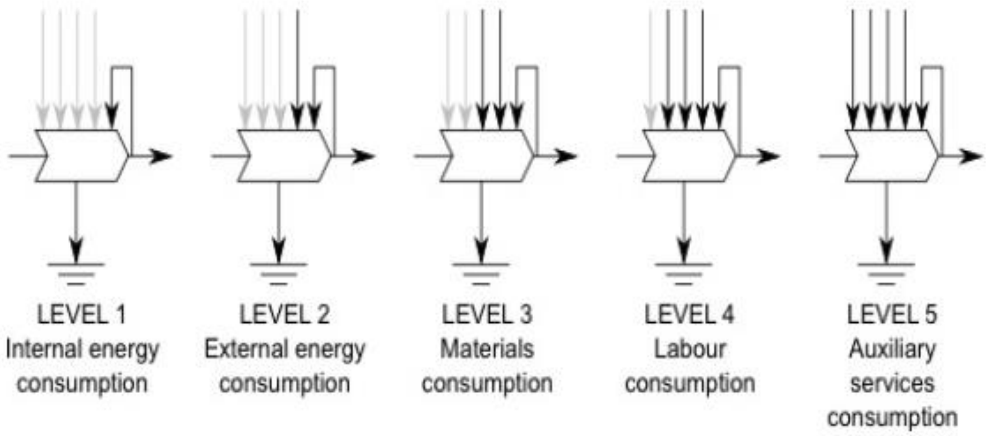


Figure 2.3: Production process with increasing levels of analysis by expansion of the system boundary to include more inputs (Murphy et al., 2011).

The EROI analysts can assess the energy flows through a particular process or product: (1) process analysis or (2) economic input-output analysis. The former is also known as bottom-up analysis and similar to lifecycle analysis, taking into account energy inputs and outputs in a process. The latter is known as top - down analysis, which converts economic input-output tables into energy units by multiplying the specific energy intensity values. A third method is a hybrid of both of these two methods, and the selection is based on where the system boundary is drawn, or data restrictions. Figures 2.2 and 2.3 support the construction of a two dimensional framework in Table 2.2 for EROI analysis (Murphy et al., 2011).

In Table 2.2, the first row represents the system boundaries for energy output, the numerator of EROI calculation; the left side of the table represents the system boundaries for energy input, the denominator of EROI calculation. The shaded cells are for those with boundaries that are convenient for economic input-output analysis, while other cells are for process-based analysis. In EROI calculation, the larger the boundary gets, the smaller the EROI will be. This is evident by the fact that the larger the boundary, the more inputs will go into the process; at the same time, energy is lost in every step after its extraction. It is suggested that all EROI studies should include at least $EROI_{stnd}$ so different studies of different fuels can be compared. $EROI_{stnd}$ includes indirect energy and material inputs and the energy retrieved in the extraction before processing which makes the EROI calculations more transparent (Murphy et al., 2011).

Table 2.2 System boundaries for energy inputs and output provided by Murphy et al., (2011).

Boundary for Energy Inputs		Boundary for Energy Outputs		
		1. Extraction	2. Processing	3. End-Use
1	Direct energy and material inputs	$EROI_{1,d}$	$EROI_{2,d}$	$EROI_{3,d}$
2	Indirect energy and material inputs	$EROI_{stnd}$	$EROI_{2,i}$	$EROI_{3,i}$
3	Indirect labor consumption	$EROI_{1,lab}$	$EROI_{2,lab}$	$EROI_{3,lab}$
4	Auxiliary services consumption	$EROI_{1,aux}$	$EROI_{2,aux}$	$EROI_{3,aux}$
5	Environmental	$EROI_{1,env}$	$EROI_{2,env}$	$EROI_{3,env}$

When calculating EROI values, it is important to adjust energy quality. The definition of energy quality is "The relative economic usefulness per heat equivalent unit of different fuels and electricity" (Cleveland et al., 2000 as cited in Murphy et al., 2009, pp.1896). In other words, it is defined that "Converting all energy inputs to common energy units using only heat equivalents assumes implicitly that a joule of oil is of the same quality as a joule of coal or a joule of electricity" (Murphy et al., 2011, p. 1896). There are two methods for adjusting energy quality: Price-Based Adjustments Method (Divisia approach) and Exergy-Based Adjustments Method. Price-Based Adjustments are based on all monetary costs to calculate energy demands, and it is recommended to use these adjustments unless there is a good reason for doing otherwise. The Exergy-Based Adjustments Method is based on exergy, which means it is based on differences in the ability to do work, and provides a method to quality-correct energy carriers based on physical units. On this account, all energy inputs are needed to do quality adjustments by using physical units. However, there are shortcomings for both methods; thus the analysts need to identify the selected method, and the benefits and shortcomings of that method before EROI calculation (Murphy et al., 2011). The reader is referred to Murphy et al. (2011) for a detailed outline of the methods.

The EROI calculation approach proposed by Murphy et al. (2011) is well adopted by (Atlason & Unnthorsson, 2013) to examine the energy efficiency at the Nesjavellir geothermal power plant to calculate its EROIs. In this study, the $EROI_{stnd}$ for the Nesjavellir geothermal power plant, as well as the $EROI_{3,i}$ are calculated. In addition, this approach was used to analyze the EROI for the Fljotsdalsstod hydroelectric power plant (690 MW), using real data of the plant. The areas of these two observations are focused on EROIs within three defined boundaries, $EROI_{stnd}$, $EROI_{3,\,i}$ and $EROI_{ide}$, (which provides the theoretical upper boundary of the EROI of a given energy conversion process). The $EROI_{stnd}$ has not been calculated for geothermal power plants and hydroelectric power plants before, so these studies can allow for future comparison (Atlason & Unnthorsson, 2014). The methodology and system boundaries set by Murphy et al., (2011) are also used in this study to predict the projected EROI values of forty-seven reservoir hydropower plants in Myanmar, and the detailed description of methodology and boundaries is addressed in Chapter 4.

2.5 Review of Typical EROI Values for Common Fuels

The various estimated values of EROI were summarized by Cleveland et al., and Hall et al., in the early 1980s; however, these estimated values were regarded as out-dated data by Murphy and Hall (2010). In 2008, Hall and twelve students observed all the available literature for the comprehensive summarization of EROI, and found very different results to those reported in Hall and Cleveland in 1986.

Cleveland (1984, 1986, and 2005) as cited in Murphy and Hall, (2010) proposed a decline in the trend of estimated EROI of drilling oil and gas in the United States. Oil had a relatively high EROI, 100 in the 1930's, but it decreased to 30 in the 1970s, and between 18 to 11 in the 2000's. According to this trend, it is estimated that the EROI trend of oil will go further downwards over time. In 2014, Hall et al. reported that EROI values for the most important fuels, world liquid and gaseous petroleum have an average EROI of about 20. The EROI for the production of oil and gas globally by publicly traded companies has decreased from 30 in 1995 to about 18 in 2006 (Gagnon et al., 2009, as cited in Hall et al., 2014). The EROI for discovering oil and gas in the US has declined from more than 1000 in 1919 to 5 in the 2010s, and for production, from about 25 in the 1970s to approximately 10 in 2007 (Guilford et al., 2011, as cited in Hall et al., 2014). However, tar sands and oil shale have lower EROI, having an average of EROI of 4 and 7 (Lambert et al., 2012). It is difficult to support EROI values for natural gas alone because the data for natural gas are integrated with oil and gas statistics (Gupta & Hall, 2011; Murphy & Hall, 2010).

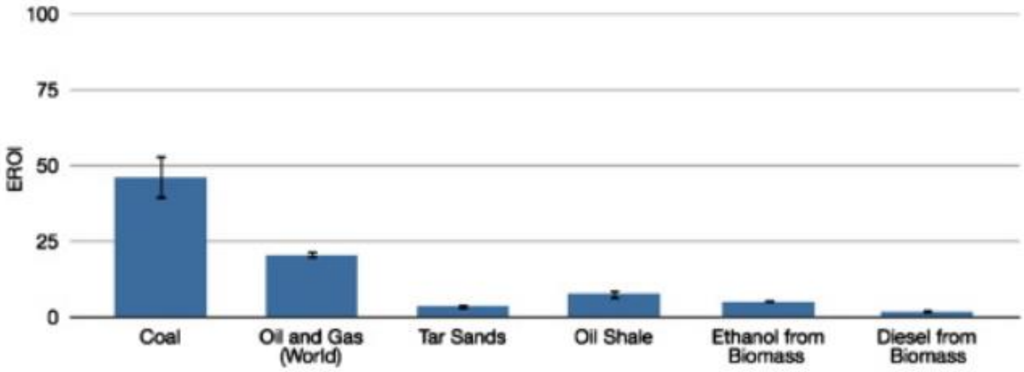


Figure 2.4 Average EROI values and standard error bars from thermal fuels reported on known values (Hall et al., 2014).

The other important fuel is coal, and the U.S. and Australia have a significantly high EROI value of coal, however, it does not show a clear trend over time. In accordance with international statistics, coal has a mean EROI of about 46:1 as shown in Figure 2.4. Cleveland et al., (2000) proposed the EROI values for coal production in the United States and there was a declination trend in coal EROIs; the value was 80 in 1950s which decreased to 30 in the 1980s. However, it climbed back to the former high EROI value of around 80 by 1990. This is a reflection of less cost in coal surface mining (Hall et al., 2014). In the case of nuclear, meta-analysis (i.e. the combined analysis results from several studies) of EROI values shows an average EROI of about 14. However, it is stated that another analyses should be conducted because the values might be affected by current technology (Hall et al., 2014). According to 50 studies involving 119 different wind farms, turbines of wind mills which have large turbines have more favourable EROI values of around 18, but they seem to have not taken into account the infrastructure costs and the highly variable nature of wind (Kubiszewski et al., 2010). However, it is noted that wind power can have high EROI values of 20, this being mainly due to the relatively small amounts of energy needed to operate turbines, and the small infrastructure. Also, the EROI value for ethanol from various biomass sources showed an average EROI value of approximately 5. The results were gathered from 31 separate publications of plant-based ethanol production (Hall et al., 2014).

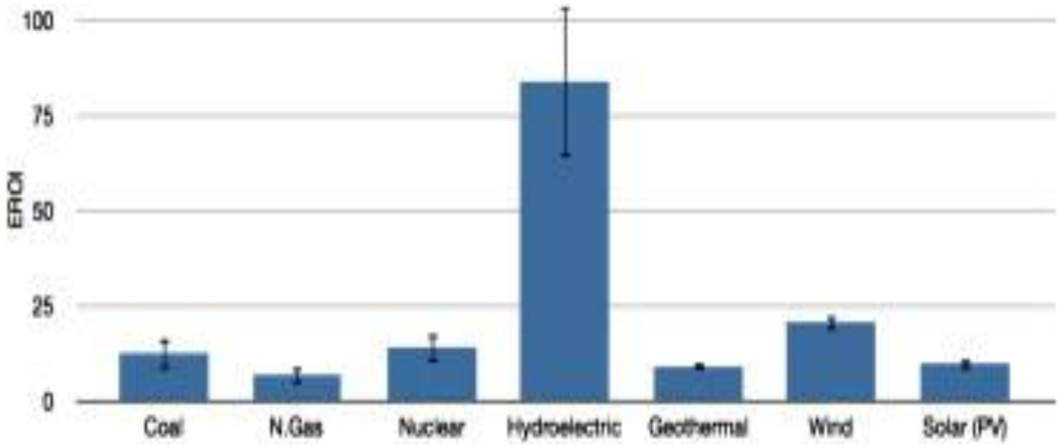


Figure 2.5 Average EROI and standard error bars for power generation systems (Hall et al., 2014).

For the EROI calculation of solar photovoltaic or PV, different assumptions and methodologies have been used, resulting in ambiguous values. However, the average supported EROI values are listed as generally 10:1. It is noted that calculations which have the broader boundaries provide EROI values of 2 to 3 (Prieto and Hall, 2012).

Among renewable and non-renewable energy sources, hydroelectric power generation systems have the highest average EROI value, 84, but the recorded EROI values of hydropower widely vary (Hall et al., 2014). The EROI of seven small scale hydroelectric power plants which have an installed capacity of less than 30 MW ranged from 8.6 to 32.9. It is stated that the reason for a power plant having the highest EROI was low capital energy costs due to little refurbishment being required, a high annual capacity factor of 69% and relatively low operation and maintenance costs. The power plant with the lowest EROI ratio was because its operation and maintenance energy costs were high (Gilliland, 1981).

It was found that a very few EROI calculations related to hydropower plants, so for this reason the EROI calculations for both run-of-river and reservoir hydropower plants are reviewed. An example of the former is the Aratiatia power station constructed on the Waitaki River in New Zealand. The installed capacity of the plant is 90 MW, which provides 270 GWh of annual energy. By using the Energy Payback Ratio which is the ratio of the output energy to the input energy, similar to EROI calculation, the power plant is expected to deliver an EROI of approximately 50 (Fernando, 2010).

The assumption of 200 years lifetime is not a reasonable one; the fact being that the materials of the dam's construction are generally affected by erosion and corrosion, thus it would be more reasonable if the life time was assumed as 100 years. In addition, instead of bottom-up analysis, the top-down analysis was used, based on a conversion of monetary costs into energy demands, therefore, the electrical energy costs cannot be observed. Moreover, the EROI result of 50 is a little difficult to apply to other hydropower plants because of the EROI's dependency on geological aspects. In other words, it is needed to consider the dam's lifetime which has a strong influence on the EROI values, so in the value of EROI might be conservative than 50. Nonetheless, it is evident that the small hydropower plant which has sub 1 MW has a lower EROI, and the large hydropower plant has a higher EROI, larger than 100 (Weiβbach et al., 2013).

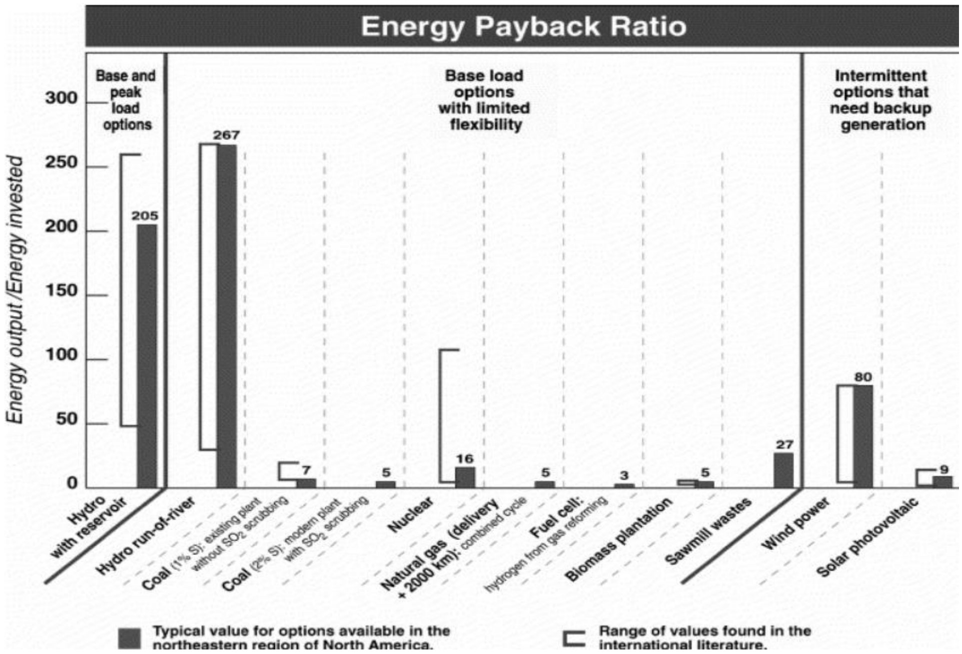


Figure 2.6 Energy payback ratio of different fuels in North America and international literature (Gagnon, 2002).

According to the assessment of hydropower projects in Quebec, the run-of-river hydropower plants have energy payback ratios of 267, while reservoir hydropower plants have 205, which mean hydropower has the highest performance amongst other renewable and non-renewable resources as illustrated in Figure 2.6. Figure shows that the EROI values as shown in international literature can be higher than those values of 205 and 267 in the north eastern region of North America (Gagnon, 2002). However, it is stated that the values were not based on any references and thus they are less plausible (Weiβbach et al., 2013).

Regarding the reservoir hydropower plant's EROI, there is a bottom-up analysis, which is likely to be a life-cycle analysis (Murphy et al., 2011). This analysis is based on the Fljotsdalsstod hydroelectric power plant in Iceland which has an installed capacity of 690 MW with an approximate annual energy of 4600 GWh. The study was focused on the real data of Fljotsdalsstod hydroelectric power plant and used the standardized methodology and system boundaries proposed by (Murphy et al., 2011) described in Section 2.4. By using different parameters within three defined boundaries, $EROI_{stnd}$, $EROI_{3,i}$ and $EROI_{ide}$ are calculated (Atlason & Unnthorsson, 2014).

Own usage by the plant, maintenance, transportation to Iceland, energy transfer infrastructure, preparation stages, construction stages and production of electrical equipment are considered as the energy input of EROI calculation. All these physical units are converted to common energy units (J) by using Exergy-Based Adjustments proposed by (Murphy et al., 2011) to convert the energy quality. Hence, energy quality is the determination of the quality of a heat unit of fuel. Due to the shortcomings of Exergy-Based Adjustments, the three different EROI results from Fljotsdalsstod power plant cannot capture the important critical input such as economic data (prices and inflation), capital and labor. The results of this calculation show that the plant is expected to deliver an $EROI_{stnd}$ of approximately 112.7, $EROI_{3,i}$ of 110.2 and $EROI_{ide}$ of 340.7 (Atlason & Unnthorsson, 2014). However, it was found that an error value was entered in $EROI_{ide}$ resulting in an $EROI_{ide}$ value of 340.7. The correct $EROI_{ide}$ value might be conservative.

2.6 Essential Features of Storage Type Hydropower Plants

This section discusses the essential features of storage type hydropower plants. These are: (1) Catchment area, (2) Reservoir, (3) Dam type, (4) Spillway, (5) Intake, (6) Water conducting system, and (7) Powerhouse, as the most important embedded energy inputs of $EROI_{stnd}$ calculation.

2.6.1 Catchment Area

Catchment Area is also called the drainage basin, in which it is defined as an area where surface water from rain or snow meet at a lower elevation, generally the exit of the basin, where the water joins with another water body for instance, river, lake, sea or ocean etc. If the reservoirs have a large catchment area, the reservoir can maintain the water above the minimum level especially in the dry season (Shaikh, 2016).

2.6.2 Reservoir

Reservoir is a water storage place which is created by constructing a dam across a river or stream together with the suitable appurtenant structures. The main function of a reservoir is not only to collect the available water from the catchment area but also to receive a portion of flood water and the excess water is discharged through the spillways. Thus, there is a relationship between the flood discharge, reservoir capacity and spillway sizes. Stored water in the reservoir creates the uniform power output throughout the year and the reservoir is governed by the amount of store water in it (Hydropower Engineering, 2015). The storage capacity in the reservoir, especially multipurpose reservoir, can be divided into three of four parts classified by the levels as shown in Figure 2.7. Hence, the cross section of the gravity dam is exemplified to describe the water levels.

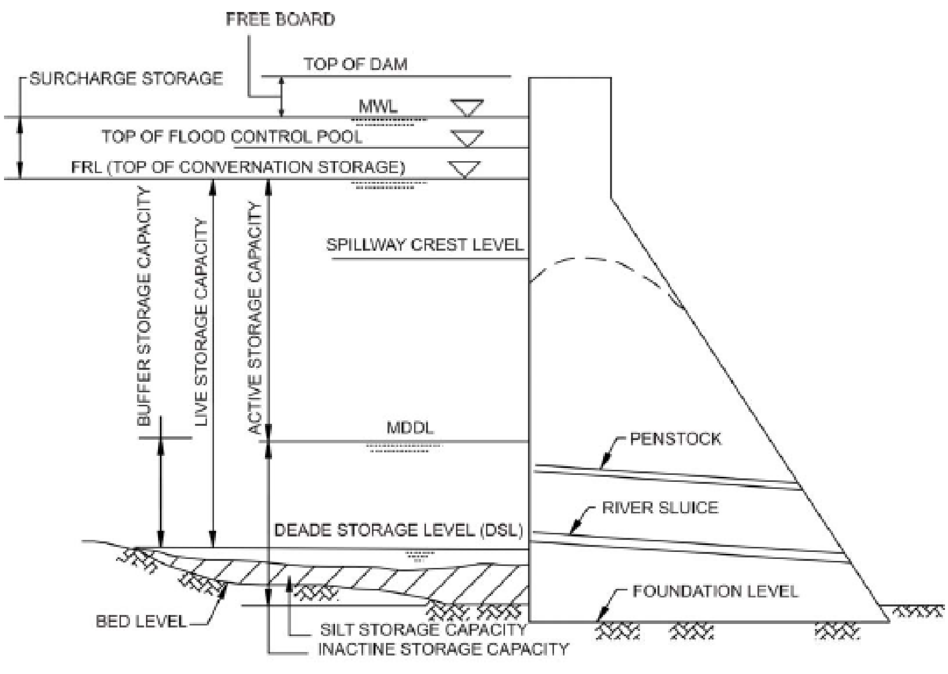


Figure 2.7 Different storage zones at the multipurpose reservoir (Hydropower Engineering, 2015).

Full Reservoir Level (FRL): The level consists of the storage which includes both active (live) and inactive (dead) storages, and also the flood storage, if it is provided for. This is the level which can be maintained without spillway discharge (Hydropower Engineering, 2015).

Minimum Drawdown Level (MDDL) – Minimum Drawdown Level (MDDL) is defined as a level that reservoir will not be drawdown the water in order to maintain a minimum head for the electricity generation projects (Hydropower Engineering, 2015).

Available drawdown: (for electricity generation purpose) is known as the vertical distance between the Full Reservoir Level and Minimum Drawdown Level (Hydropower Engineering, 2015).

Dead Storage Level (DSL): It is defined as the level in which below this level, there are no outlets to drain the water by gravity (Hydropower Engineering, 2015).

Maximum Water Level (MWL): The water level that is ever likely to be attained during the passage of the design flood and depends on the specified initial reservoir level and the spillway gate operation rule. This level can also call as the Highest Reservoir Level or the Highest Flood Level (Hydropower Engineering, 2015).

Live storage: Live storage is defined as the water volume in reservoir which is available at any time. The live storage level is between the Dead Storage Level and the lower of the actual water level and Full Reservoir Level" (Hydropower Engineering, 2015).

Dead storage: Dead storage is the total storage under the invert level of the lowest discharge outlet from the reservoir which is also available to maintain sedimentation, if the sediment does not affect the lowest (Hydropower Engineering, 2015).

2.6.3 Dams

Gravity dam and embankment dam are two main types of reservoir dams which have been developed for hydropower generation purposes. The gravity type dam can be a conventional placed mass concrete dam, roller compacted concrete (RCC) dam, curved gravity dams (arch action) or buttress dam (U.S Army Crops, 1995). The embankment dam can be an earth-fill dam or rock-fill dam (U.S Army Crops, 2004). For gravity dam types, conventional placed mass concrete dam and roller compacted concrete dam will only be focused on as the main concerns of this study. For embankment dam types, both earth and rock-rill dams will be covered in this study.

2.6.3.1 Gravity Dam

Gravity dam can be defined as a solid concrete structure, and its own weight resists the major and minor external forces acting on it. Although masonry and concrete were used to build gravity dams in the past, today's preferred materials are Conventional Vibrated Concrete (CVC) for conventional placed mass concrete dams and Roller Compacted Concrete (RCC) for RCC dams (Tandon, 2014; U. S. Army Corps, 1995; Awan, 2014). This section discusses materials and construction procedures for both dam types. Hence, for the composite dam type, (which dam structure consists of a section of a concrete gravity dam within an embankment dam for overflow (spillway) section), the concrete section can be designed according to these procedures. Therefore, there is no specific discussion on it.

2.6.3.2 Materials and Construction Procedure of Conventional Placed Mass Concrete Dam

In the case of conventional placed mass concrete dam construction, Conventional Vibrated Concrete (CVC) is used as a material for proportioning, mixing, placing, curing and temperature control of mass concrete. The unit weight of concrete for the dead load of a gravity dam can be assumed 2403 kg/m^3 (150 lb/ft^3), unless it is indicated otherwise. For dam construction, it is necessary to use large-size coarse aggregates to produce a low-slump concrete which provides economy, maintains good workability during placement, develops minimum temperature rise during hydration, and produces important properties such as strength, impermeability and durability (US Army Corps, 1995).

As concrete is generally produced from aggregates (rock and sand), hydraulic cement and water, a typical concrete contains a large amount of coarse and fine aggregates, a moderate amount of cement and water and a small amount of admixtures. The aggregates are crushed, washed and dried, thus a modest amount of energy is involved in the process. The total embodied energy used in the production of concrete is 0.893 MJ/kg which is the highest amount of embodied energy in the Portland cement manufacturing process. Portland cement is manufactured by heating a mixture of limestone and shale in a kiln up to 1500˚C. After that, it is inter-ground, resulting in clinker with gypsum to produce a fine powder. Thus, Portland cement has a higher embodied energy than others, resulting in high embodied energy of CVC (Struble & Godfrey, 2004). The utilization of CVC facilitates the installation of conduits, penstocks and galleries within the dam structure (US Army Corps, 1995).

Before the construction of a dam, the water of the river needs to be diverted. For this purpose, a diversion tunnel or diversion open channel can be constructed to divert the entire flow around the dam site in terms of the geological and topographical conditions. The construction work should be close to cofferdams, which are temporary structures built around part or all of the excavation for a dam or other structures to create a dry work environment. The diversion tunnel or channel will start from the upstream cofferdam and join with the river again on the downstream site (Tandon, 2014, U.S Army Corps, 1995).

In the case of dam construction, there could be two scenarios; the first one being that the water in the river is diverted to one side of the river channel by constructing a semi-circle type of a coffer dam, and the work can proceed in the water free-zone of the river side. After constructing the half of dam length, the remaining half width of the river channel is closed by building another coffer dam. The river flow can be diverted through the dam outlets or overtopped the constructed portion of the dam. The work will proceed in the water-free zone (Tandon, 2014).

A large volume of concrete is produced at an onsite batch plant, thus requiring a sufficient source of large size coarse aggregates to be located at or within an economical distance of the project. Then, the concrete is transported from the batch plant to the dam by using buckets sizing from 3.06 to 9.17 cubic metres and carried by truck, rail, cranes, cableways or a combination method (U.S Army Corps, 1995). As the construction stage, concrete is placed in lifts (layers) of 1.52 to 3.05 metre depths. Lift means that the concrete is poured up to a certain height. Each and every lift consists of successive layers, 0.46 to 0.51 metres. Then, the vibration process is continued by large one-man or air-driven vibrators or spud-type vibrators. The weak laitance film on the surface of horizontal construction joints need to be cleaned and removed during the curing process by green-cutting, using wet sand-blasting and high-pressure air-water jet (US Army Corps, 1995).

The placement of concrete in the gravity dam is generally in blocks, and the size of those blocks depends on the size of the dam, and contraction joints are needed to prevent cracking of the concrete. Those blocks are called monoliths, and the width of monoliths is 15 m or so, above for large dams and maximum height is around 1.5 m or so (Tandon, 2014).

During the placement of concrete, a tremendous amount of heat is liberated due to cement hydration which increases the temperature inside the body of the dam. However, the dam's outside temperature remains the same according to the atmospheric temperature. According to the temperature differences, temperature stresses develop in the dam body. Moreover, due to shrinkage of concrete as it cools, shrinkage stresses also develop. These temperature and shrinkage stresses will cause cracking in the concrete if appropriate remedial measures are not taken (Tandon, 2014).

To avoid unnecessary cracks, various measures can be taken, including using a minimum amount of cement in a given mix of specified strength. The quantity of cement can be decreased by better grading of the aggregates. In addition, lower lifts can also be used for concrete. If the lifts are reduced, more horizontal joints will develop and also sufficient cooling time between two successive pours should be allowed to reduce cracking. Another method is providing suitable spaced contraction joints in addition to the normal construction joints (Tandon, 2014). Heat generation can be controlled by using precooling and post-cooling techniques to limit the temperature range (US Army Corps, 1995). Another way that cooling can be done is by circulating cold water through pipes which are embedded in the concrete, however this method is used only in large gravity dams because of the expense (Tandon, 2014).

2.6.3.3 Materials and Construction Procedure of Roller Compacted Concrete Dam

Roller Compacted Concrete (RCC) is simply defined as "A relatively dry concrete material that has been consolidated through external vibration from vibratory rollers" (US Army Corps, 1995, page. B - 3). The difference between CVC and RCC is the mixture consistency and method of compaction. For CVC concrete, immersion type vibrators are used for an internal compaction process, while RCC concrete, spreading equipment and vibrator rollers are used in the external compaction process. Although proportioning procedures are similar for both, RCC concrete contains less water and more fly ash (Bauchkar & Chore, n.d). The aim of the mixing design is to get an RCC mixture that has sufficient paste volume for coating the aggregates in the mix and filling in the voids between them (Rashed, 2015). The mixture design for RCC includes fine and coarse aggregates, cementitious materials (cement and fly ash, especially dry, lean, zero slump concrete material) and coarse and fine aggregate, water and admixture (Bauchkar & Chore, n.d; US Army Corps, 1995). The unit weight of RCC can have slight differences in terms of RCC placement in different zones; however it can generally be specified as 2420 kg/m^3 (Barga et al., 2003).

The aggregates' sizes used in Roller-Compacted Concrete (RCC) are often the same as those for CVC concrete. However, the blending of aggregates is different from that of CVC. Crushed aggregates are more preferable in RCC mixture due to the sharp interlocking edges of the particles for reducing segregation and providing higher strength. Although washed aggregates are not needed for this type, the content of fine particles requirement is much higher than that of CVC (Rashed, 2015). The involvement of aggregates is approximately 75 % to 85 % of the volume of RCC, resulting in the fresh and hardened concreted properties. The suitable selections of aggregates do need to provide the economic benefits and durability of RCC. Both fine (finer than 4.75 mm) and coarse aggregates can be used in RCC mixtures (Bauchkar & Chore, n.d).

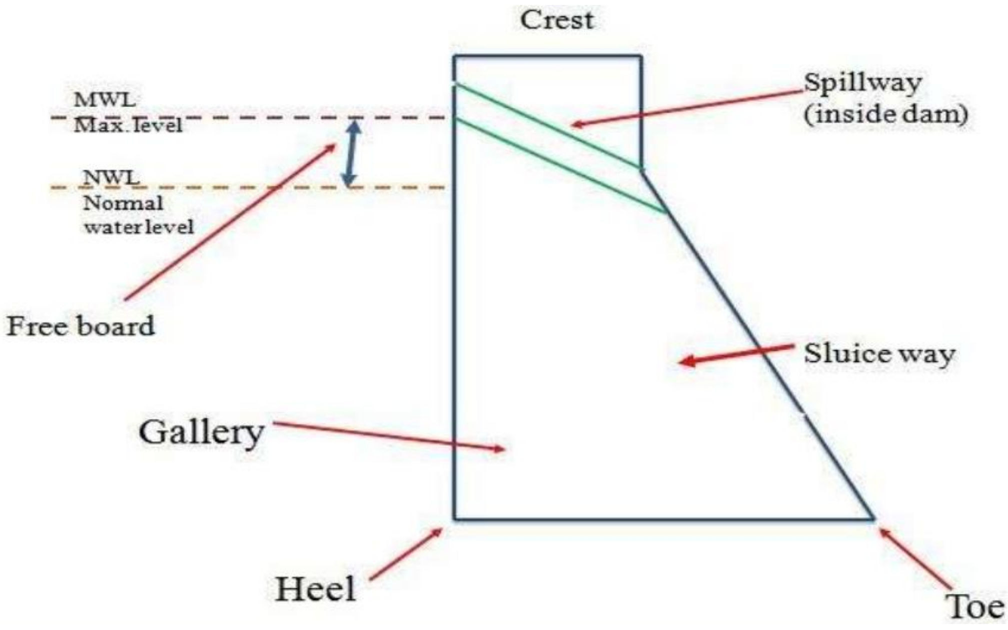


Figure 2.8 Typical cross section of RCC dam (Tandon, 2014).

The utilization of cementitious materials used in RCC are Portland cement or blended hydraulic cement, and can include pozzolan, or a ground granulated blast furnace slag according to the requirement of strength. The use of pozzolan in RCC mixtures can be as a partial replacement for cement to reduce heat generation, to reduce cost, or to provide supplemental fines for mixture workability and paste volume. Cement replacement can be varied from none to 80 percent in terms of mass. In some cases, a large amount of pozzolan is used to replace Portland cement for reducing internal temperature rise which causes thermal stresses. In terms of the mix proportioning methods of RCC, there is no generally accepted procedure. Several methods use different approaches around the world (Bauchkar & Chore, n.d).

Generally, the construction of a RCC dam is relatively new in terms of technical and economic points of view. One of the benefits of the RCC construction placement method is a much lower unit cost per cubic yard by comparison with conventional concrete placement methods. Due to the dry and non-flowable nature of RCC, wide range of equipment can be used for the construction and placement process. RCC concrete can be transported from the mixer to the dam by using end and bottom dump trucks and or conveyors. RCC must be dry enough in the case of effective consolidation in order to assist the weight of the construction equipment, however, it should be wet enough to assist adequate distribution during the mixing and vibration process, and thus, it will achieve the necessary compaction of RCC. In addition, it can also avoid unnecessary segregation and voids (US. Army Corps, 1995). Mechanical spreaders, such as caterpillars and graders are used to place the material in layers or lifts. Self-propelled, vibratory, steel-wheeled, or pneumatic rollers along with the dozers perform the compaction process in the dam construction. The thickness of the placement layers, ranging from 0.20 to 0.61 metres are compacted and placed continuously. According to the flexibility, RCC dams can be constructed at relatively higher rates than conventional mass concrete dam (US. Army Corps, 1995).

2.6.3.4 Embankment Dams

Embankment dams are defined as the dams built by using natural materials. The construction designs were mostly based on experience in the past; however, today embankment dams are designed based upon utilizing a wide knowledge of soil behavior and the advancement of soil machineries. By utilization of these resources, today's embankment dams can be built up to the height of 300 m (Virajian, 2014; Tandon, 2014). In this section, materials and construction procedures for embankment dams (earth and rock-fill dams) will be discussed.

2.6.3.5 Materials and Construction Procedure of Earth Dams and Rock-fill Dams

Embankment dams can be constructed using all types of geologic materials except organic soils and peats. Generally, most of the embankment dams are designed to use on-site materials as a bulk construction; however, the materials used in special zones such as filter can come from off-site sources (United States Society on Dams, 2011).

Suitable soils for embankment dams construction can come from borrow areas of sites or excavated soils, these are transported from the borrow pits to the dam sites by trucks or scrapers (United States Society on Dams, 2011; US Army Corps, 2004). Most of the embankment dams are constructed from broadly graded soils including fine grained soils and coarse-grained soils. Fine grained soils can be defined as materials which have at least 50 % by weight of particles finer than 0.074 mm, and they are classified as either clay or silts. Among them, clay soil is more likely to be used because it is less permeable than silty soil. They can be used as the water barrier in the embankment dams, either in a homogeneous section, or as the core in a zoned embankment. Coarse grained soils include gravels and sands; sands are defined as soils finer than 4.76 mm and gravels are those coarser than 4.76 mm and finer than 76.2 mm. Gravels and sands typically are used in the shells or in transition zones of zoned embankments, and in filters and drains. Gravels and sandy gravels are sometimes used as the primary section of an embankment with an upstream facing of asphaltic concrete or Portland cement concrete (United States Society on Dams, 2011).

At the construction stage, soils such as soft sandstone are broken down into soil as the first stage of earth-fill dam construction. After that, the dumped soils are spread at the dam site by bulldozers to get between 15 to 45 cm thicknesses (US Army Corps, 2004). Materials in the embankment shells, excluding filter and drain zones should be compacted to maximum practicable densities. Heavy, vibratory compaction equipment generally works best. Moisture control is not as critical for gravels, gravelly sands, silty sands, and sandy gravels, as it is for fine grained materials (United States Society on Dams, 2011). Each and every layer is compacted by tamping rollers; sheep foot rollers, heavy pneumatic tired rollers, vibratory rollers, tractors, or earth hauling equipment. During the compaction process, each layer is sprinkled with water to get the Optimum Moisture Content (OMC). The whole process of soil placement is known as the rolled fill method which is a common type of earth dam construction method (Virajian, 2014; Tandon, 2014; US Army Corps, 2004).

Rock-fill dams are constructed with a large amount of rock as an impervious core. A series of transition zones are built by using suitably graded materials between core and rock shells. The size of rock can vary from smaller stones to 3 m. The rock-fill zones are compacted layer by layer in the thickness of 12 to 24 inches by using heavy rubber-tired or steel wheel vibratory rollers. The most suitable methods of construction and compaction can be decided from the test quarry and test fill results. If the dam is built on a rock foundation, free draining and well compacted rock fill is suitable for placing with steep slopes. If the dam is built on an earth or weathered rock foundation, the slope should be flatter and transition zones are needed to be placed between the foundation and the rock-fill (US Army Corps, 2004).

The materials required for Concrete Faced Rock-fill Dam (CFRD) are aggregates; cement and additives for concrete, earth-fill for upstream fill, granular fill for filters, rock-fill or gravel fill for the main body of the embankment, water stop to seal the joints in the concrete slab, and asphalt and shot Crete or other materials for protection of the slope under the concrete face slab. The concrete requirement is similar to the requirements for conventional concrete. Generally, maximum size of aggregate to 38 mm can be used, however, a maximum size aggregate of 68 mm has sometimes been used and is satisfactory with special care taken at the construction and contraction joints, and water stops. The cement used in the concrete is usually Portland cement. Pozzolan, fly ash and plasticizer are used to reduce the water cement ratio and to minimize the long term risk of alkali reactivity. It is considered good practice to use pozzolan or fly ash even with apparently non-reactive aggregates to provide a more impervious and durable concrete. For concrete facing, it is reasonable to use a face slab of constant thickness of 30 cm for dams of low to moderate height of 50 to 70 m and to use an incremental thickness of about 0.002 times the height for important and high dams (United States Society on Dams, 2011).

2.6.4 Spillway

Reservoir can store a certain capacity of water in it. When the reservoir is full and the flood water comes into it the same time, the water level in the reservoir goes up and it can eventually exceed the height of the dam. Spillways are provided to draw water from the top of the reservoir to release the flood waters to the downstream site (Hydropower Engineering, 2015). Generally, they are embedded in the gravity dam body, whereas they can also be separated from the dam if the dam is the embankment type as shown in Figure 2.9 (A) and (B), and 2.10 (Ministry of Electric Power, 2015).

Figure 2.9 (A) Spillways embedded in the gravity dam body (Yeywa), (B) Water flows through the gated type spillways (Thanphanseik) (Ministry of Electric Power, 2015).

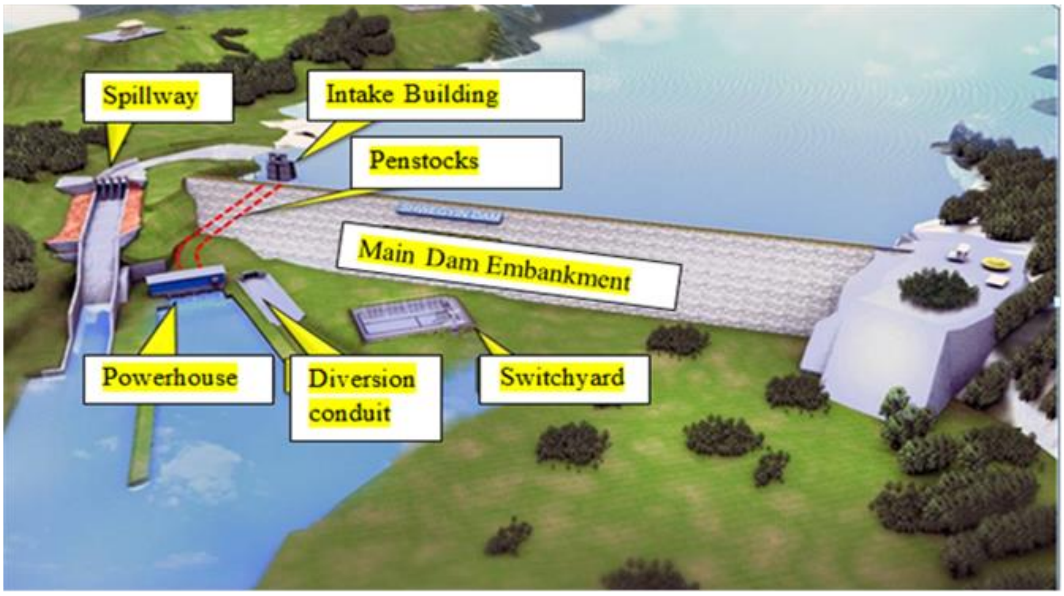


Figure 2.10 Side channel spillway separated from the embankment dam body (Shwegyin) (Ministry of Electric Power, 2015).

Spillways can be gated (controlled) or un-gated (uncontrolled) type. The controlled spillways have more advantages than uncontrolled ones. When the reservoir is at the full situation, the water level in the reservoir is the same as the spillway's crest level which is called the normal reservoir level (Full Reservoir Level-FRL). If the flood enters into the reservoir at this time, the level of water goes up, and then starts flow through the spillway. The water level rising continue for some time and it will discharge over the spillway. After reaching the maximum stage, the reservoir level comes down and then finally come back to the normal reservoir level (Hydropower Engineering, 2015).

The dam top is higher than the maximum reservoir level corresponding to the design flood for the spillway. The surcharge storage can be defined as the storage available between the maximum water level and normal reservoir level (FRL) as shown in Figure 2.8. This surcharge storage is a temporary storage in un-gated spillway types. However, in a gated spillway type, water is stored above the spillway crest level by closing the gates of the spillway. Then, the gates can be reopened again when a flood has passed. Therefore, gated spillways types can store water more than un-gated type even the dams have the same height (Hydropower Engineering, 2015).

For design consideration, it is needed to consider the inflow design flood hydrograph, type of spillway and its capacity, energy dissipation at the downstream of spillway etc. Spillway consists of a combination of control structure and channel, and a terminal structure. The most common types of spillway are Ogee spillway, Chute (Trough) spillway and Side channel spillway (Hydropower Engineering, 2015).

2.6.5 Intakes

Intakes for storage type hydropower plants can be in the form of a conduit or a form of tower depending on the variation of the water level in the reservoir. Trash Rack is provided at the entrance of the intake to screening the debris and the floating materials into the water conducting system. Intake gates are also called the inlet gates which are constructed inside the dam to control the flow of water. They are also called the inlet gates. When these gates are opened, the water enters into the power generation unit due to gravity through steel penstocks. The life expectancy of intake gate and intake screen is 50 years and 35 years respectively (MESA Associates, 2012). Tower intake structures and trash rack systems are shown in Figure 2.11 (MESA Associates, 2012).

Figure 2.11 Tower intake structures and trash rack systems (MESA Associates, 2012).

2.6.6 Water Conducting System

Water passes through the water conducting system after it comes out from the intake structure. The conducting system can be either closed conduit or open-channels. The system consists of headrace, surge tank, penstock and tailrace (Hydropower Engineering, 2015). A typical section of water conducting system is shown in Figure 2.12.

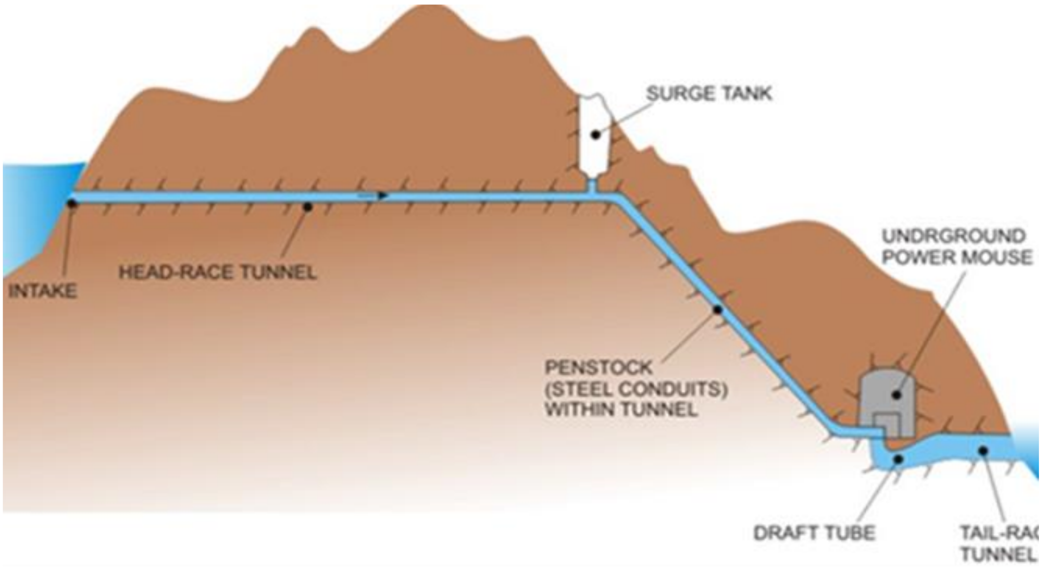


Figure 2.12 A Typical water conducting system of a hydropower plant (Hydropower Engineering, 2015).

(a) Headrace

According to the layout of a hydroelectric plant, it is required a tunnel to convey water through the mountains (HRT). Head Race Tunnel (HRT) can be defined as the initial portion between the intake and surge tank, and after surge tank, it connects to the steel conduit penstock which involves a larger pressure than HRT. The HRT can be either unlined or lined with the concrete according to the surrounding quality of rock. If it is lined with the concrete due to the poor quality of rock, the reinforcement in the concrete lining assists to prevent fallout of rock blocks into the tunnel. If the rock above the tunnel is very weak, the tunnel need to support a larger rock weight in which the suitable reinforcement design is needed (Hydropower Engineering, 2015).

(b) Surge Tank

The surge tank prevents the penstocks from bursting because of the sudden pressure changes. The load on the turbine can be changed suddenly due to the action of the governor, such as the turbines input gates are closed according to the necessaries of the electricity load. In that case, a sudden stop of water happen at the lower end of penstock, and the excess water is pushed back to the surge tank and the water level at the surge tank is increased. Therefore, the surge tank is a preventive tool to protect the penstock's bursting condition due to the high pressure variation by increasing the water level in it Surge tank can be served as either a supply tank or a storage tank for the turbines by adjusting the load conditions. It functions as a supply tank to the turbines when the water in the penstock is accelerated due to increased load conditions. It functions as a storage tank when the water in the penstock is decelerated due to reduce load conditions. It has a preventive function for not only the water hammer effect of the penstock but also the protective function for the upstream tunnel, HRT from the high pressure rise. The water hammer effect is defined as the sudden pressure changes above or below normal pressure in the rate of water flow through the pipe (Hydropower Engineering, 2015).

(c) Penstock

Penstocks are generally defined as the steel or reinforced concrete lined conduit that convey water from the reservoir, (or through headrace tunnel and surge tank if they are provided) to the turbines. The penstocks must withstand very high pressure of water thus their design looks like the pressure vessels and tanks. The penstocks are designed to withstand the water hammer pressure because of the sudden closure of the valves at the turbines due to the necessary load fluctuations. As part of the water conducting system, these pressurized conduits are designed to reduce the least possible head loss of energy. Penstocks are generally made up with mild steel. If the diameter is larger, they are fabricated from welded steel plates together (Hydropower Engineering, 2015). Penstocks are classified three types based on the location of penstocks on the ground surface: exposed, embedded and underground type. Exposed penstocks are located above the ground which are supported by the pier, saddle or ring grinder. Embedded penstocks are buried in the tunnel. Underground penstock can be partially or fully buried. The life expectancy of penstocks is estimated between 40 to 60 years (Wieland, 2016). According to the waterway system, penstock can be a single feeding unit or branching which is defined as bifurcation that generally involves two symmetric pipes for two feeding units or trifurcation, three feeding units as the manifold of the turbines units as shown in Figure 2.13 (Hydropower Engineering, 2015).

Figure 2.13 Penstock single feeding, bifurcation and trifurcation (Energypedia, n.d).

(d) Tailrace

As shown in Figure 2.14, the tailrace surge tank is provided if the hydropower system is underground to prevent the tailrace tunnel from the water hammer effect because of load fluctuation. However, the tail race surge tank can be eliminated in the case of tunnel free-flow conditions.

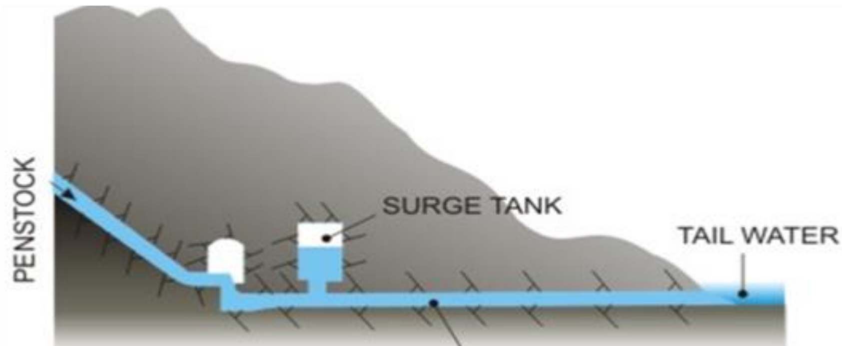


Figure 2.14 Surge tank in tail race tunnel (Hydropower Engineering, 2015).

The consideration of tunnels should be carefully designed and constructed so as to get the best performance. There are four tunnel sections types, circular section, D section, Horse-Shoe section and ellipse shaped sections, in which the horse-shoe section types are strong enough to resist the external pressures and also the covered rock good quality is safe enough to prevent the tunnel internal pressure. The horse-shoe section provides not only the constructional ease due to the flat base but also assist the minimum expenditure if the rocks are inadequate or poor rock formations (Hydropower Engineering, 2015).

2.6.7 Powerhouse

Three types of powerhouse are surface powerhouse or above ground power house, semi-underground powerhouse and underground powerhouse as shown in Figure 2.15 (Ministry of Electric Power, 2015). In the surface powerhouse or above ground type, all the components are above the excavated ground surface. The benefit of this power house type is pre-determined topography, design and easy to construct whereas the disadvantage is the limitation of head due to the topography. In this type, the water inlet can be from a penstock or from a tunnel and the water outlet flows to the tailrace. In the semi underground type, some parts of the powerhouse are underground, and some are on the ground surface. The benefits of both surface and underground type can be found in this type if the topography and geology are allowed at the plant site. If the power house is located inside the mountain due to the topography of the plant site, it is called the underground powerhouse and all the equipment is located in the cavern. The capital cost for this type is uneconomical because it is needed to build a lot of tunnels such as headrace tunnels for water inflow, tailrace tunnels for water outflows and other kind of various tunnels are needed to be built in the mountain (Alizay, 2013).

Figure 2.15 Above ground type (Nan Cho), semi-underground type (Sedawgyi) and underground type Powerhouse (Paunglaung) (Ministry of Electric Power, 2015).

2.7 Conclusions

The concepts of Carbon Emissions Pinch Analysis (CEPA) techniques and Energy Return of Investment (EROI), with special attention to the methodology and system boundaries of EROI analysis have been reviewed in this literature. The analyses of EROI results for different fuel types especially EROI results of hydropower plants are also presented. The essential features of storage type hydropower plants also have been generally discussed as an important part of EROI's Energy input calculation. Special attention will now be given to the hydropower resources in Myanmar in Chapter 3 and the detailed discussion of storage type hydropower plants will be addressed.

Chapter 3
Hydropower Resources in Myanmar

3.1 Introduction

Myanmar has tremendous hydropower potential; however the majority of this potential has remained undeveloped due to the economic and political disturbances. The technical feasible potential from the major rivers and other potential water resources support the country as one of the renewable energy rich countries amongst its neighbouring, energy demand countries especially China, and India. Due to the increase in electricity demand of the domestic and cross border regional energy trade issues (Kattelus et al., 2015), the necessity for the extraction of the large hydropower resources should be fulfilled from the geopolitical perspective. In this chapter, the current situation and future potentials of hydropower resources, based on storage type hydropower plants on the major rivers will be addressed. The detailed elements' information of all those power plants is also presented to proceed as the fundamental data of EROI calculation.

3.2 Development of Hydropower Resources on Major Rivers

The headwaters of the Ayeyarwady River are May Kha and Mali Kha Rivers originate in the south-eastern Himalayas, and then join as a confluence at a height of 147 m about 50 km north of Myitkyina, the capital city of Kachin state situated in the country's northern part. The three major tributaries, Chindwin River, Shweli River and Myitnge River meet the Ayeyarwady and then it flows through the central heartland of the country. At the downstream side, the river passes through a nine-armed delta and empties into the Andaman Sea in the Bay of Bengal. In total, the country's longest river, the Ayeyarwady is 2210 km long. Due to the warm sub-tropical climate in the upper basin to humid tropical climate in the lower basin and strong variation in precipitation, the Ayeyarwady River flow pattern varies throughout the year between 2300 m^3/s and 32600 m^3/s, with the annual average discharge of 13000 km^3 (Simmance, 2013). Figure 3.1 shows the major rivers in Myanmar, Ayeyarwady (previous name is Irrawaddy), Chindwin, Sittaung, and Thanlwin and River (Wikipedia: Irrawaddy River, 2016).

Currently, the hydropower developed capacity on the Ayeyarwady River is about 8 % of its total hydropower potential as shown in Table 3.1 (Khaing, 2015a). In terms of capacity, the total developed capacity in 2015 is 3151 MW and the installed capacity of under-construction power plants are 2398.40 MW (Khaing, 2015a). Figure 3.2 shows the different level of storage type hydropower plants on the Ayeryarwady River. Figure 3.3 shows 380 MW a stage storage type hydropower plant on Chindwin River at the under-processing stage (Ministry of Electric Power, 2015). It is noted that run-of river power plants and some storage type hydropower plants location are not described on the figures due to the data unavailability for EROI calculation.

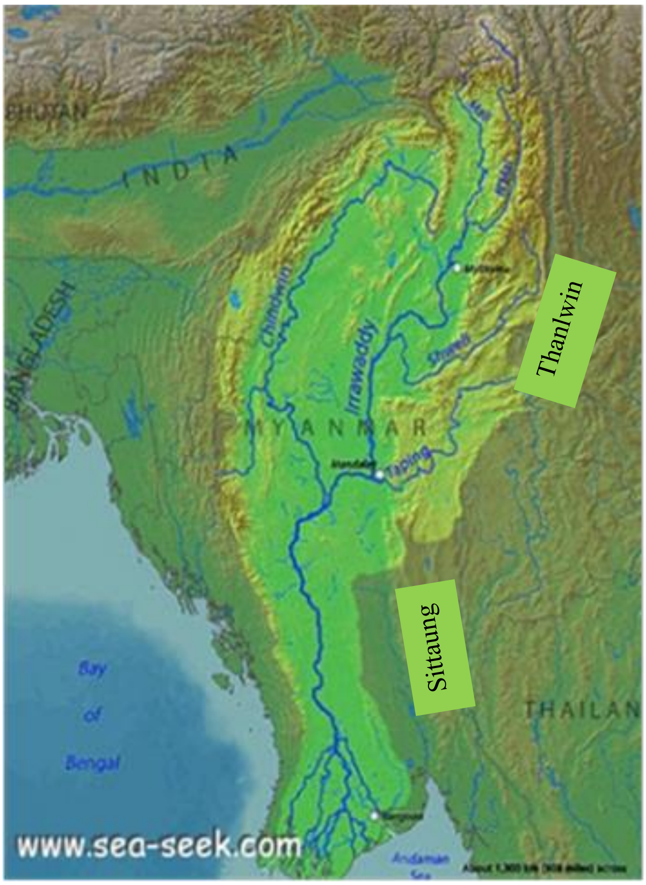


Figure 3.1 Myanmar location map and its major rivers (Wikipedia: Irrawaddy River, 2016).

Sittaung River with a catchment area of 34400 km^2 rises at the Shan Plateau, and flowing southward and emptying into the Andaman Sea (Van Rest, 2015). The total length of the Sittaung River is 420 km. The river mainstream surface is almost the same size along the river but the tributaries have a larger surface and a flow pattern of this river is a fairly flat. The rivers average discharge rate is 1542

m^3/s and annual discharge is 42 km^3. Due to the climatic variation conditions, the water resources in the river are duplicitous throughout the year (de Vilder, 2015).

Table 3.1 Hydropower potentials on major river basins (Khaing, 2015a).

Rivers	Developed Capacity (MW)	Under Construction (MW)	Under Processing (MW)	Future Potentials (MW)	Total Potential (MW)
Ayeyarwady	2019	2206	15200	6000	25425
Chindwin	-	-	380	1860	2240
Sittaung	830	-	260	-	1090
Thanlwin	302	81.40	15395	765	16543.40
Others	-	111	521	1511.50	2143.50
Total (MW)	3151	2398.40	31756	10136.50	47441.90

As stated in Table 3.1, about 76% hydropower potential of the Sittaung River had been developed by 10 hydropower plants, 830 MW (Khaing, 2015a). These constructed hydropower plants location are shown in Figure 3.4. There is no under-construction stage power plant on the Sittaung River (Ministry of Electric Power, 2015). Although the under processing capacity is 260 MW, only one storage type hydropower plant at the under-construction stage is described in Figure 3.4. It is noted that the developed capacity 3151 MW is the capacity from medium and large hydropower plants which is not included developed capacity from small hydropower plants, that is 34.174 MW in 2015 (Ministry of Electric Power, 2015).

Thanlwin River originates in the Tibetan Plateau, part of the Himalayan mountain ranges and flows through China's Yunnan province into three States of Myanmar, and forms the border between Thailand and Myanmar before re-entering Myanmar, then empties into the Andaman Sea. The Thanlwin River is the world's 26th longest river as well as the second largest river in Southeast Asia after Mekong River. The River has a total length of 2820 km, in which 1100 km is within Myanmar's border (Longcharoen & Panapraisakun, 2014). The total area of trans-boundary Thanlwin River is 320000 km^2, in which China is sharing (169600 km^2, 53 %), Myanmar is sharing (134400 km^2, 42%) and Thailand is sharing (16000 km^2, 5%). The annual flow of the Thanlwin river basin from China to Myanmar is 68.74 km^3 and Myanmar and Thailand border is 200 km^3/year. The hydropower resources of Thanlwin River and its tributaries are tremendous, but the potential resources are far from the community (Food and

Agriculture Organization of the United Nations, 2016). Although the Thanlwin River has huge hydropower potential, the developed capacity is just around 2 %, 302 MW as shown in Table 3.1. The under-construction plants capacity is 81.40 MW while tremendous capacity, 15395 MW is at the under processing stage (Khaing, 2015a). Figure 3.5 shows the Thanlwin River hydropower schemes (Ministry of Electric Power, 2015).

Besides Ayeyarwady, Chindwin, Sittaung and Thanlwin River Hydropower schemes, there are some other hydropower potentials as Separate River Valleys Projects at the western part of Myanmar, and as trans-boundary Mekong River hydropower schemes at the eastern part of Myanmar, those are described as “others” in Table 3.1 (Khaing, 2015a). Figure 3.6 shows the under-processing stage storage type hydropower plant, 111 MW on Thahtay creek, one of the Separate River Valleys Projects (Ministry of Electric Power, 2015).

Mekong River is the world’s 12th longest river which rises at the Tibetan Plateau, at a height of over 5000 m and flows through Tibetan Autonomous Region in the north and southeast into China’s Yunnan Province. After that it flows through the Three Parallel Rivers Area, along with the Yangtze and Thanlwin River. Mekong is a trans-boundary river flow through China, Myanmar, Laos People Democratic Republic (Laos), Kingdom of Thailand and Vietnam. The river is also the 7th longest river in Asia with a total length of 4350 km. The drainage area of the whole Mekong basin is 795000 km^2. Average annual discharge is 16000 m^3/s and maximum discharge is 39000 m^3/s. Myanmar’s drainage basin area is about 3 % of the total Mekong’s basin area, 24000 km^2 and Mekong river length within Myanmar is 350 km with a total catchment area of 28600 km^2 (Mekong River Commission, 2010). The hydropower potential in the whole Mekong river basin is estimated at 53000 MW, in which about 5% has been developed (ICEM, 2010). Six hydropower plants have been built by China on the Mekong River whereas another 14 hydropower plants are proposed by China. Eleven hydropower plants are planned on the Mekong tributaries by Laos (The Economist, 2015). The installed capacity of storage type hydropower plants proposed by Myanmar is 511 MW which is at the under processing stage. The power plants locations are shown in Figure 3.7 (Ministry of Electric Power, 2015). Mekong trans-boundary River is shown in Figure 3.8 (Mekong Report, 2015).

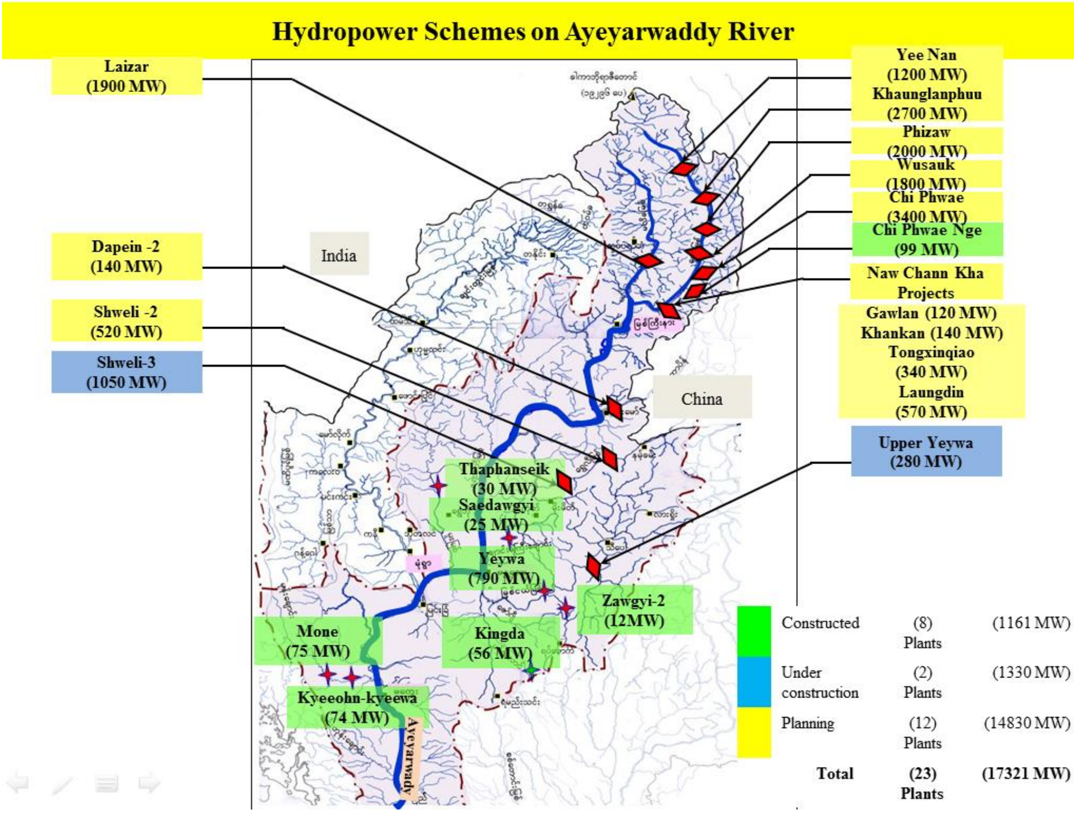


Figure 3.2 Hydropower schemes on Ayeyarwady River (Ministry of Electric Power, 2015).

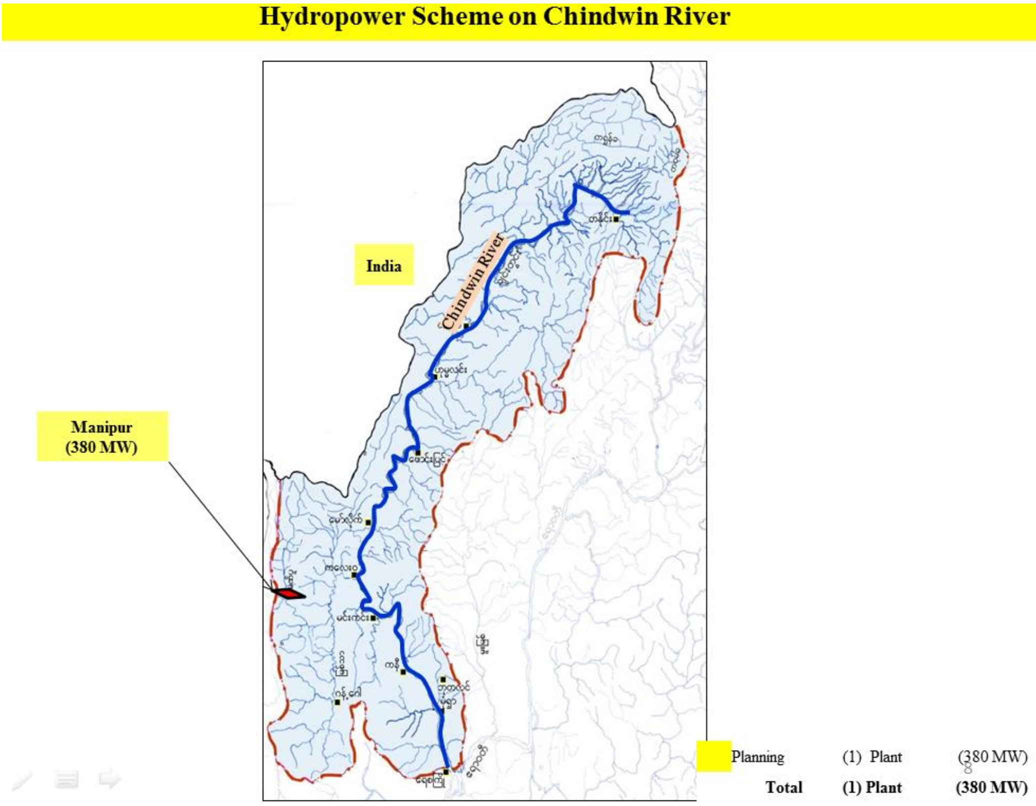


Figure 3.3 Hydropower scheme on Chindwin River (Ministry of Electric Power, 2015).

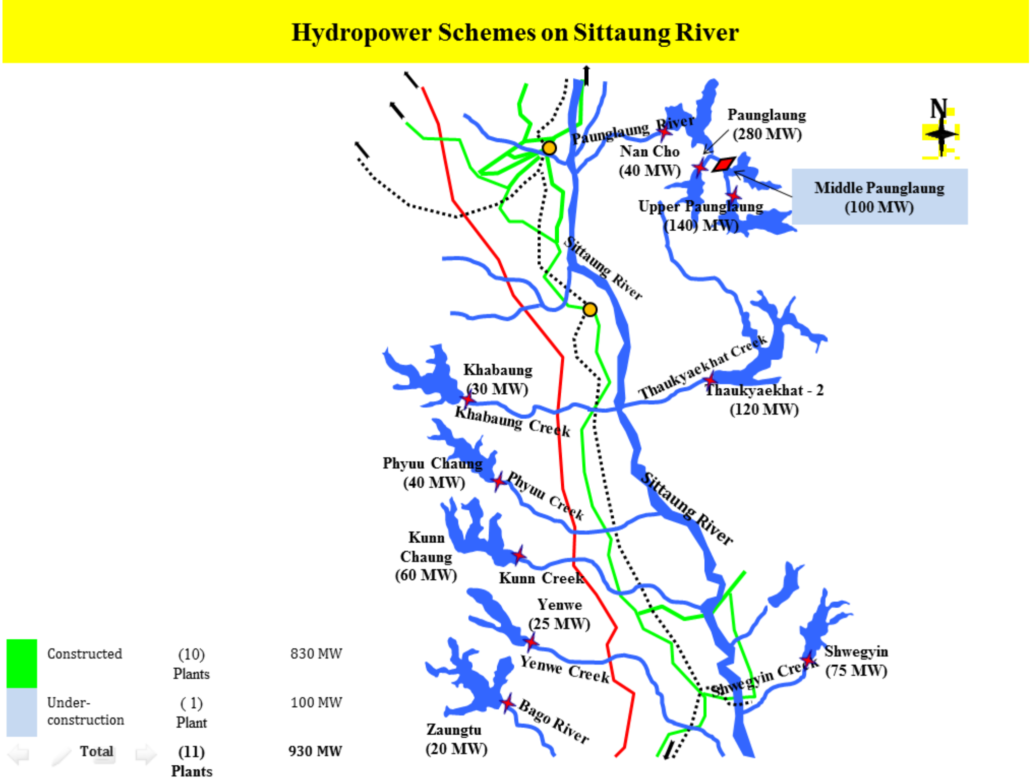


Figure 3.4 Hydropower schemes on Sittaung River (Ministry of Electric Power, 2015).

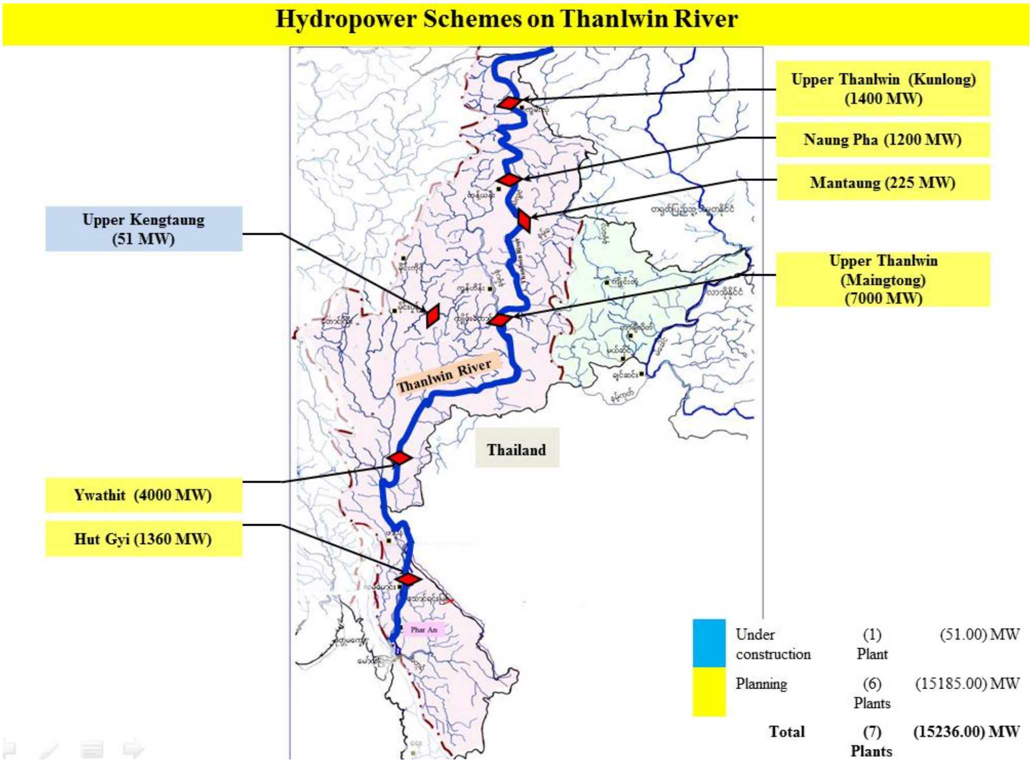


Figure 3.5 Hydropower schemes on Sittaung River (Ministry of Electric Power, 2015).

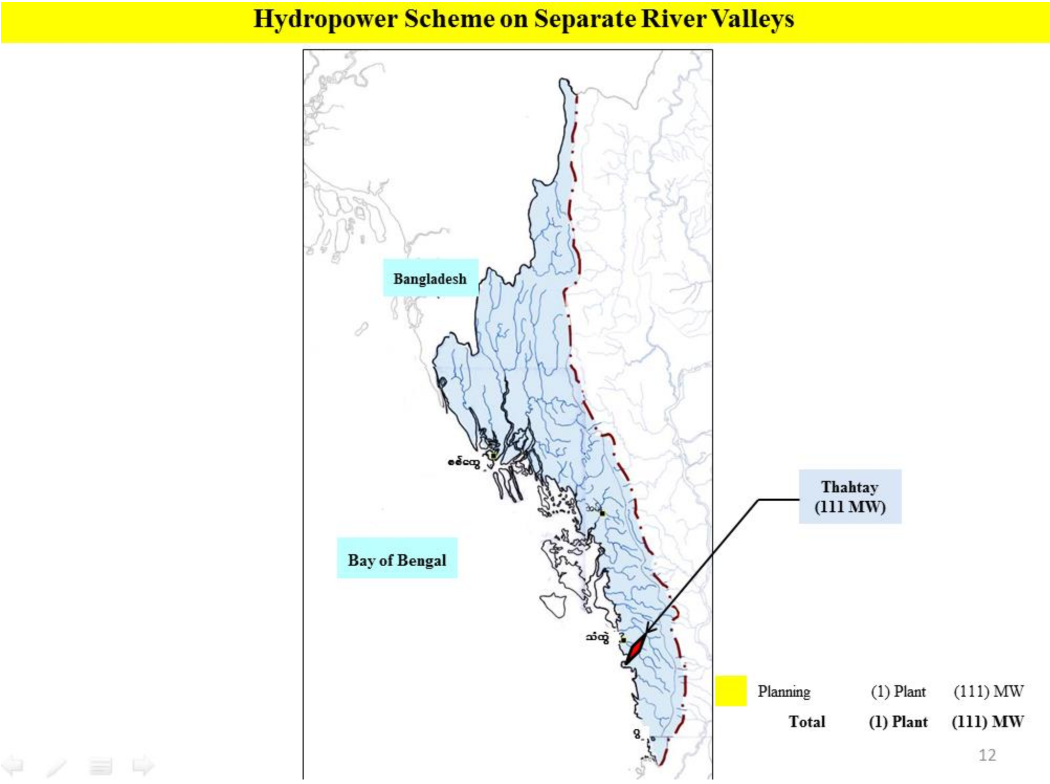


Figure 3.6 Hydropower scheme on Separate River Valleys (Ministry of Electric Power, 2015).

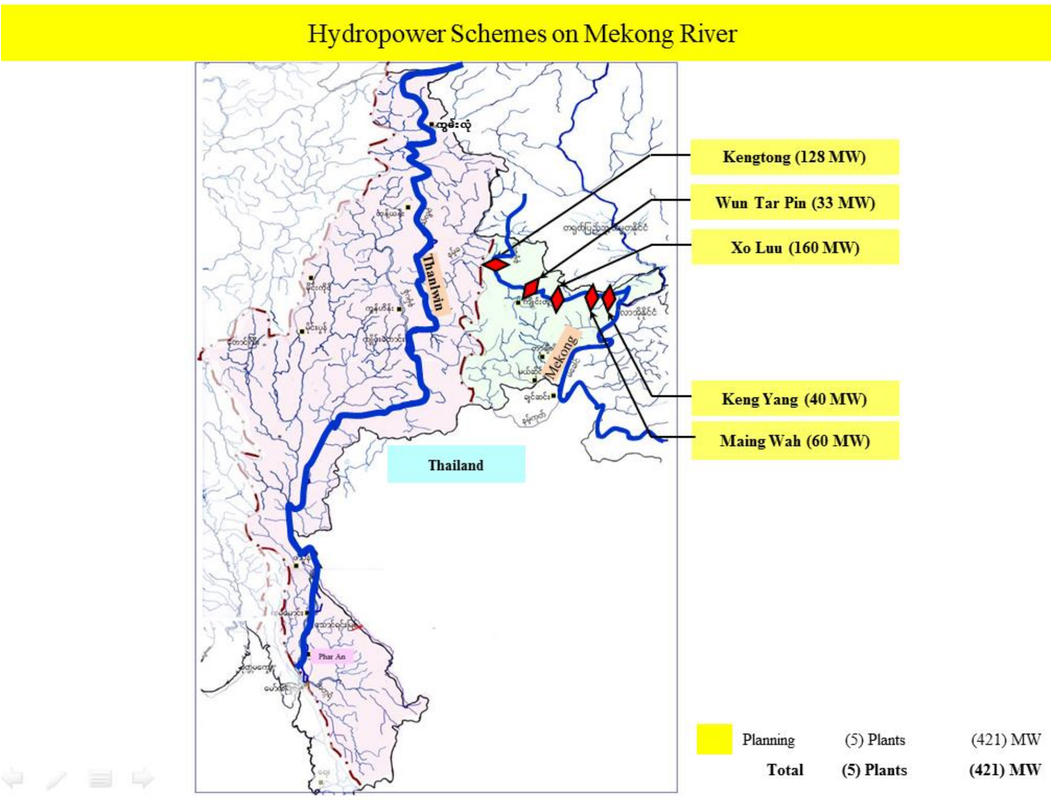


Figure 3.7 Hydropower schemes on Mekong River (Ministry of Electric Power, 2015).

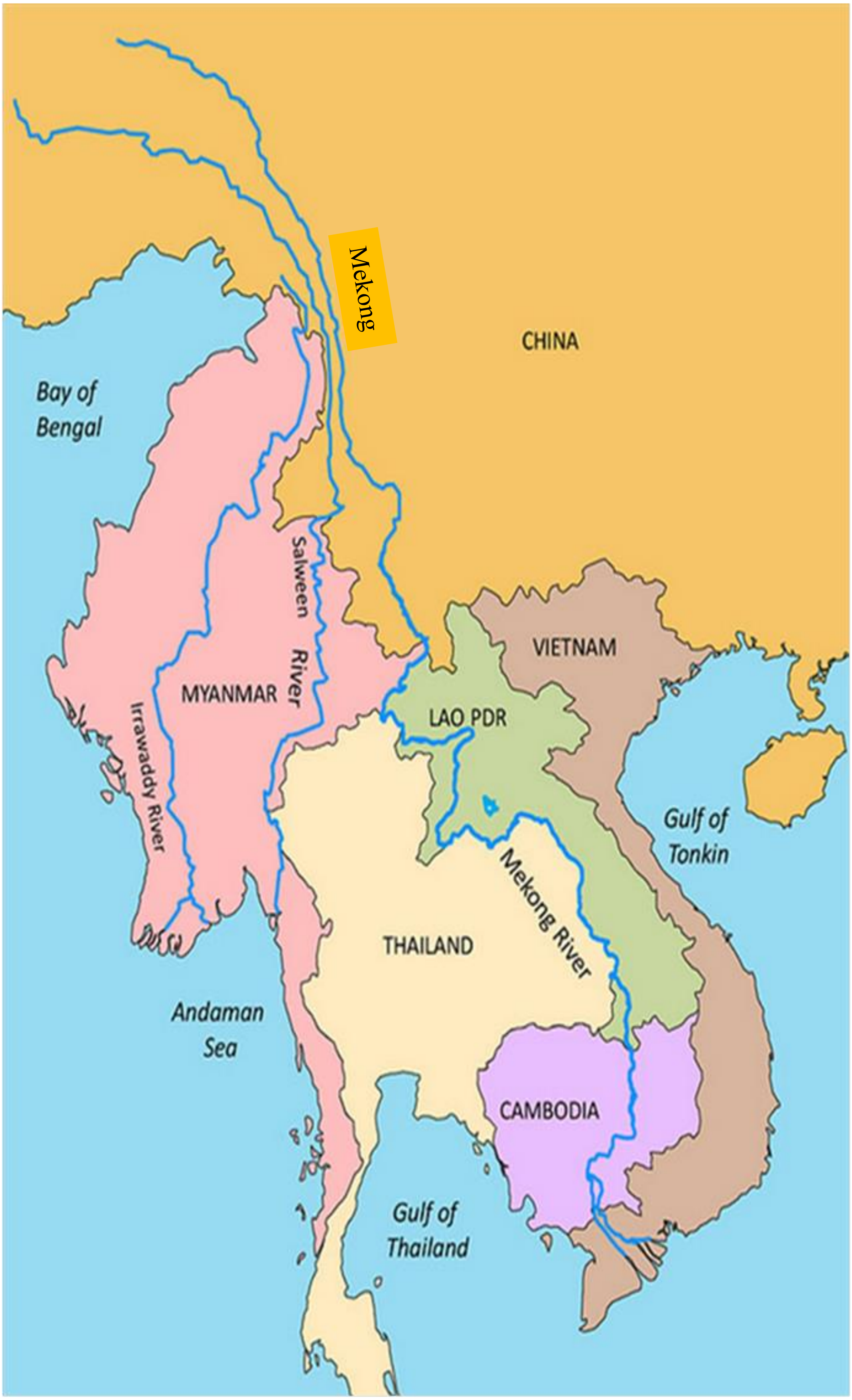


Figure 3.8 Mekong Trans-Boundary River (Mekong Report, 2015).

3.3 Hydropower Plants in Myanmar

Hydropower plants can be classified in accordance with size (small, medium or large), head (low, medium or high), facility types (run-of-river, storage or pumped storage), purpose (single purpose or multipurpose), hydropower relations (single project or cascade project) and transmission system (isolated or grid connected) (Kaunda et al., 2012, Bairwa, 2014).

Based on the level of installed capacity, as the hydropower plants can be grouped as small, medium and large, the definition can differ from countries to countries (Kaunda et al., 2012). Myanmar considers 10 MW as the limits for small hydropower plants, between 10 MW and 30 MW as the medium hydropower plants and above these limits are large hydropower plants (Ministry of Electric Power, 2015).

Head can be generally defined as a different water level between inlet (headrace) and outlet (tailrace) of the plant, and sorted into low, medium and high head. The classification of head can also be different from countries to countries (Kaunda et al., 2012). Head can be classified by analysing volumetric flow rate at each turbine (V°, m^3/s) and types of turbines. Generally, Pelton turbines are used for high head (between 300 m and 4000 m) and low flow rate (below 35 m^3/s) , Kaplan turbines are used for low head (below 30 m) and high flow rate (between 70 m^3/s and 300 m^3/s), and Francis turbines are widely used for medium head (between 30 m and 300 m) and medium flow rate (between 35 m^3/s and 70 m^3/s), high head and medium flow rate, and medium head and high flow rate (Hydropower Engineering, 2015). Vertical Francis turbines are widely used in most of the hydropower plants in Myanmar due to the head variations and volumetric flow rate at the turbines (Ministry of Electric Power, 2015).

Based on the level of water, hydropower plants can be categorized as three main types, run-of-river, reservoir (storage hydro) and pumped storage types. As storage type hydropower plants have more energy benefits compared to run-of-river plants the fact that they can store potential energy behind the dam leading to generate electricity to adjust the base load and peak load of the electricity demand (Kaunda et al., 2012). Storage type hydropower plants on the Ayeyarwady and Sittaung River are constructed to implement this purpose. In addition, multipurpose projects can bring many benefits for society not only electricity generation but also flood control, irrigation, and water supply. Most storage type hydropower plants on the Ayeyarwady and Sittaung Rivers are multipurpose projects intended for the economic growth of the irrigation purposes. However, adverse effect is that hydroelectricity generations from those projects are prioritized as the secondary objective. As a result, the annual electricity generation can sometimes below the targeted generation because of the irrigated areas are prioritized to supply water from the reservoirs, leading to the head variations in the reservoirs (Electrical Industry of Burma, 2012).

One of the advantages of storage hydropower projects is the ability to regulate water in the downstream site of the dam throughout the year. It means the reservoir plant at the upstream site of the river can increase the reliability of power generation for the plant at the downstream site because the water from the upstream site plant is regulated the downstream site water throughout the year (Kaunda et al., 2012). By using this concept, the cascade projects such as run-of river cascade projects, run-of river and storage type cascade projects, and storage type cascade projects were built as the Ayeyarwady, Sittaung and Thanlwin River hydropower schemes (Electrical Industry of Burma, 2012).

Table 3.2 illustrates the classification of the 25 constructed hydropower plants and 5 under construction power plants based on the above-mentioned features. Due to the data accessed from MOEP, 8 constructed hydropower plants are medium sized power plants. Seventeen out of 25 constructed hydropower plants and 5 under-construction power plants (from No.26 to No.30) are large scale plants. The low head power plants which have “head” lower than 30 m are 3 power plants, whereas high head power plants which have “head” higher than 400 m are 2 power plants. The other power plants are medium head power plants, “head” between 30 m and 400 m. Based on the power plants specific locations concerned with the head and flow rate at the turbines, Vertical Francis turbines are widely used. There are two power plants that use Pelton turbines due to very high head and low flow rate. Vertical Kaplan turbines are also used for low head and either low flow rate or medium flow rate at four power plants. In terms of the facility type, the number of storage type hydropower plants is more than run-of river types, in which seven power plants are run-of river types. As hydropower relations, cascade projects are more constructed than single projects in order to take advantage of increasing water flow rate from the upstream reservoirs. Thirteen out of 17 constructed storage type hydropower plants are multipurpose projects in order to support the irrigated areas for the development of agricultural sector.

According to the "National Electricity Master Plan" (2014-2030) proposed by JICA et al., 2014, the installed capacity of Myanmar electricity sector is estimated about 28 GW in 2030. The detailed explanation will be carried out in Chapter 4. Based on this master plan, the hydropower installed capacity is also extended as the majority of the renewable electricity generation. Table 3.3 illustrates the classification of 24 planned storage type hydropower plants with the total installed capacity of 30816 MW.

It is obvious that the installed capacities of most of the planned power plants are significantly larger than those of the constructed and under-construction power plants. Hence, all the power plants are large scale hydro in which only three power plants' installed capacities are less than 100 MW while 10 power plants have the installed capacity between 100 MW and 600 MW. The other 11 power plants have very high installed capacity between 1200 MW and 7000 MW due to the significant high flow rate at each turbine of the power plants, regardless of either low head or medium head. Those high capacity power plants are also located on the main stream of the respective rivers resulted in the high flow rate other than the rest of the power plants. Vertical Francis turbines types are widely used in most of the power plants because of the variations of head and flow rate. All the future projects are single purpose storage type with cascade hydropower relations (Ministry of Electric Power, 2015 & Myint, 2015a, b).

Table 3.2 Classification of constructed and under-construction hydropower plants (Ministry of Electric Power, 2015).

No.	Projects	Installed Capacity (MW) (Small/ Medium/ Large)			Volumetric flow rate for a turbine (V˚- m³/s)	Type of turbines	Head (m) (Low/Medium/High)		Facility Type (Run-of/ Storage)	Hydro power relations (Single/ Cascade)	Purpose (Single/Multi-purpose)
1	Zawgyi 2	12	2 × 6	Medium	25.00	Vertical Francis	40.54	Medium	Storage	Cascade	Multipurpose
2	Zawgyi 1	18	3×6	Medium	6.20	Horizontal Francis	117.00	Medium	Run-of	Cascade	Single
3	Zaungtu	20	2 × 10	Medium	43.50	Vertical Kaplan	27.40	Low	Storage	Single	Multipurpose
4	Sedawgyi	25	2 × 12.5	Medium	49.50	Vertical Kaplan	28.23	Low	Storage	Single	Multipurpose
5	Yenwe	25	2 × 12.5	Medium	25.00	Vertical Francis	57.00	Medium	Storage	Single	Multipurpose
6	Baluchaung 1	28	2 ×14	Medium	23.79	Vertical Francis	70.00	Medium	Run-of	Cascade	Single
7	Thaphanseik	30	2 ×15	Medium	76.59	Vertical Kaplan	19.00	Low	Storage	Single	Multipurpose
8	Khabaung	30	2 × 15	Medium	39.50	Vertical Francis	46.33	Medium	Storage	Single	Multipurpose
9	Nan Cho	40	2 × 6	Large	24.00	Vertical Francis	100.00	Medium	Storage	Single	Multipurpose
10	Phyuu Chaung	40	2 × 20	Large	35.96	Vertical Francis	115.00	Medium	Storage	Single	Multipurpose
11	Baluchaung 3	52	2×26	Large	25.48	Vertical Francis	121.31	Medium	Run-of	Cascade	Single
12	Kengtaung	54	3×18	Large	50.00	Vertical Francis	47.00	Medium	Run-of	Cascade	Single
13	Kinda	56	2 × 28	Large	56.00	Vertical Francis	56.00	Medium	Storage	Single	Multipurpose
14	Kunn Chaung	60	3 × 20	Large	31.51	Vertical Francis	105.77	Medium	Storage	Single	Multipurpose
15	Kyeeohn Kyeewa	74	2 × 37	Large	121.65	Vertical Kaplan	34.29	Medium	Storage	Cascade	Multipurpose
16	Mone	75	3 × 25	Large	57.00	Vertical Francis	47.24	Medium	Storage	Cascade	Multipurpose
17	Shwegyin	75	4×18.75	Large	54.00	Vertical Francis	42.00	Medium	Storage	Single	Single
18	Chi Phwae Nge	99	3 × 33	Large	8.80	Vertical Pelton	433.00	High	Storage	Single	Single
19	Thaukyaekhat 2	120	3 × 40	Large	70.00	Vertical Francis	65.00	Medium	Storage	Cascade	Multipurpose
20	Upper Paunglaung	140	2 × 70	Large	100.00	Vertical Francis	79.00	Medium	Storage	Cascade	Single
21	Baluchaung 2	168	6 × 28	Large	7.93	Horizontal Pelton	423.00	High	Run-of	Cascade	Single
22	Dapein 1	240	4 × 60	Large	96.50	Vertical Francis	69.19	Medium	Run-of	Cascade	Single
23	Paunglaung	280	4 × 70	Large	76.50	Vertical Francis	103.63	Medium	Storage	Cascade	Single
24	Shweli 1	600	6 ×100	Large	37.62	Vertical Francis	300.00	Medium	Run-of	Cascade	Single
25	Yeywa	790	4×197.50	Large	245.00	Vertical Francis	105.00	Medium	Storage	Cascade	Single
26	Upper Kengtaung	51	3 ×17	Large	150.00	Vertical Francis	47.00	Medium	Storage	Cascade	Single
27	Middle Paunglaung	100	2 × 50	Large	110.00	Vertical Francis	55.00	Medium	Storage	Cascade	Single
28	Thahtay	111	3 × 37	Large	210.00	Vertical Francis	62.48	Medium	Storage	Single	Single
29	Upper Yeywa	280	4 ×70	Large	500.00	Vertical Francis	67.00	Medium	Storage	Cascade	Single
30	Shweli 3	1050	4×262.50	Large	1321.40	Vertical Francis	90.00	Medium	Storage	Cascade	Single
	Total	**4743**									

Table 3.3 Classification of planned hydropower plants (Ministry of Electric Power, 2015 & Myint, 2015 a, b).

No.	Projects	Installed Capacity (MW) (Small/ Medium/ Large)			Volumetric flow rate for a turbine (V°- m^3/s)	Type of turbines	Head (m) (Low/Medium/High)		Facility Type (Run-of/ Storage)	Hydro Power Relations (Single/ Cascade)	Purpose (Single/Multi-purpose)
1	Wun Tar Pin	33	2 × 16.50	Large	72.26	Vertical Kaplan	26.50	Low	Storage	Cascade	Single
2	Keng Yang	40	2 × 20	Large	196.61	Bulb Tubular	11.50	Low	Storage	Cascade	Single
3	Maing Wah	60	3 × 20	Large	91.10	Vertical Kaplan	25.60	Low	Storage	Cascade	Single
4	Gawlan	120	2 × 60	Large	38.20	Vertical Francis	175.00	Medium	Storage	Cascade	Single
5	Kengtong	128	2 × 64	Large	50.29	Vertical Francis	143.00	Medium	Storage	Cascade	Single
6	Dapein 2	140	2 × 70	Large	190.00	Vertical Francis	41.45	Medium	Storage	Cascade	Single
7	Khankan	140	2 × 70	Large	64.65	Vertical Francis	130.00	Medium	Storage	Cascade	Single
8	Xo Luu	160	2 × 80	Large	125.00	Vertical Francis	73.00	Medium	Storage	Cascade	Single
9	Mantaung	225	3 × 75	Large	101.00	Vertical Francis	85.00	Medium	Storage	Cascade	Single
10	Tongxinqiao	340	2 × 170	Large	72.90	Vertical Francis	260.00	Medium	Storage	Cascade	Single
11	Manipour	380	4 × 95	Large	86.00	Vertical Francis	123.75	Medium	Storage	Cascade	Single
12	Shweli 2	520	4 × 130	Large	131.50	Vertical Francis	110.00	Medium	Storage	Cascade	Single
13	Longdin	570	3 × 190	Large	59.00	Vertical Francis	355.00	High	Storage	Cascade	Single
14	Yee Nan	1200	3 × 400	Large	370.00	Vertical Francis	122.53	Medium	Storage	Cascade	Single
15	Naung Pha	1200	6 × 200	Large	500.00	Vertical Francis	45.11	Medium	Storage	Cascade	Single
16	Hutgyi	1360	8 × 170	Large	648.08	Vertical Kaplan	30.00	Low	Storage	Cascade	Single
17	Kunlong	1400	4 × 300 1 × 200	Large	620.32 412.93	Vertical Francis	54.00	Medium	Storage	Cascade	Single
18	Wusauk	1800	4 × 450	Large	490.00	Vertical Francis	120.70	Medium	Storage	Cascade	Single
19	Laizar	1900	4 × 475	Large	548.00	Vertical Francis	98.00	Medium	Storage	Cascade	Single
20	Phizaw	2000	4 × 500	Large	469.00	Vertical Francis	120.70	Medium	Storage	Cascade	Single
21	Khaunglanphuu	2700	4 × 675	Large	398.00	Vertical Francis	192.02	Medium	Storage	Cascade	Single
22	Chi Phwae	3400	5 × 680	Large	541.00	Vertical Francis	104.00	Medium	Storage	Cascade	Single
23	Ywathit	4000	8 × 500	Large	661.20	Vertical Kaplan	32.30	Medium	Storage	Cascade	Single
24	Maingtong	7000	10 × 630 2 × 350	Large	246.58	Vertical Francis	268.00	Medium	Storage	Cascade	Single
	Total	**30816**									

3.4 Hydropower Potential Power Output and Outlook

3.4.1 Hydropower Potential

As the main characteristics of hydropower potentials, flow (Q) and head (H) can be defined by Equation (3.1) as follows:

$$P_{Hydro} = C_p \times H \times Q \tag{3-1}$$

Where, C_p is a constant and defined as the hydropower coefficient. The power production of a plant is controlled by the flow (Q) which is only one variable due to the fact that the head cannot be increased for most of the hydropower plants except head is modified in some cases (Kaunda et al., 2012).

3.4.2 Power Output

There is a certain amount of energy loss during the energy conversion process of a hydropower plant because of using turbines and generators. The power out P is defined as follow:

$$P = \rho g Q H_e \eta \times 10^{-3} \tag{3-2}$$

Where, P is Power output (kW), ρ is the water density = 1,000 (kg/m^3), g is free fall acceleration = 9.8 m/s^2, Q is flow or power discharge (m^3/s), H_e is the effective head which is the same as head, H in Equation 3.1, (m) and η is the combined efficiency of turbine and generator (Mizuta & Takeda, 2015).

3.4.3 Generation

The electric energy (Power × Time) generated by continuous operation of P (KW) for T hours (h), is defined as the generated energy and the unit is kilowatt hour (KWh). "The electric energy generated for one year at the power plant is called the annual energy generation or annual energy production" (Mizuta & Takeda, 2015). The capacity factor of the hydropower plants can vary, in which capacity factor is "the amount of actual electricity generated by a power station for a specified period of time over the electricity the power station would have generated in the same period if the power was being generated at the ideal power rating" (Kaunda et al., 2012, pg. 8). Ideal power rating is the same as the nameplate rating on the generator. For a hydropower system, capacity factor relies on both the availability of water for power generation and peaking load or based load of a plant. Capacity factor is not ever being 100% because the plants shut down for maintenance purposes and responds to the electricity demand fluctuation (Kaunda et al., 2012).

Table 3.4 illustrates the power output (installed capacity), combined efficiency of turbine and generator calculated by Equation (3.2), annual energy generation (GWh) and capacity factor (the ratio of actual power and installed capacity) for 18 constructed and 5 under-construction storage type hydropower plants (Ministry of Electric Power, 2015). Table 3.5 shows those data of 24 planned storage type hydropower plants. As illustrated in Tables, the power plants' installed capacity range from the lowest 12 MW with annual energy generation 30 GWh to the highest 7000 MW with annual energy generation 34717 GWh. The capacity factors can be ranged from the lowest, 0.29 to the highest, 0.63 whereas most planned power plants which have high annual energy generation generally have high capacity factor rather than other power plants.

Table 3.4 Hydroelectric characteristics of constructed and under-construction storage type hydropower plants (Ministry of Electric Power, 2015).

No.	Level	Projects	Installed Capacity (MW)	Combined Efficiency	Annual Energy Generation (GWh)	Actual Power (MW)	Capacity Factor
1	In operation	Zawgyi 2	12	0.77	30	3.42	0.29
2	In operation	Zaungtu	20	0.85	76.30	8.70	0.44
3	In operation	Sedawgyi	25	0.91	134	15.29	0.61
4	In operation	Yenwe	25	0.90	123	14.03	0.56
5	In operation	Khabaung	30	0.87	120	13.69	0.46
6	In operation	Thaphanseik	30	0.85	117.20	13.37	0.45
7	In operation	Nan Cho	40	0.90	152	17.34	0.43
8	In operation	Phyuu Chaung	40	0.87	120	13.69	0.34
9	Under-construction	Upper Kengtaung	51	0.74	267	30.46	0.60
10	In operation	Kinda	56	0.91	165	18.82	0.34
11	In operation	Kunn Chuang	60	0.88	190	21.67	0.36
12	In operation	Kyeeohn Kyeewa	74	0.76	370	42.21	0.57
13	In operation	Mone	75	0.95	330	37.65	0.50
14	In operation	Shwegyin	75	0.87	262	30.00	0.40
15	In operation	Chi Phwae Nge	99	0.88	599	68.33	0.69
16	Under construction	Middle Paunglaung	100	0.87	500	57.04	0.57
17	Under construction	Thahtay	111	0.86	386	44.03	0.40
18	In operation	Thaukyaekhat 2	120	0.89	604	68.90	0.57
19	In operation	Upper Paunglaung	140	0.90	454	52.00	0.37
20	In operation	Paunglaung	280	0.90	911	104.00	0.37
21	Under-construction	Upper Yeywa	280	0.85	1409	160.00	0.57
22	In operation	Yeywa	790	0.91	3550	405.00	0.51
23	Under-construction	Shweli 3	1050	0.91	3400	388.00	0.37
	Total		**3583**		**14269.50**		

Table 3.5 Hydroelectric characteristics of planned power plants (Ministry of Electric Power, 2015 & Myint, 2015a, b).

No.	Level	Projects	Installed Capacity (MW)	Combined Efficiency	Annual Energy Generation (GWh/y)	Actual Power (MW)	Capacity Factor
1	Planned	Wun Tar Pin	33	0.88	170	19.38	0.59
2	Planned	Keng Yang	40	0.90	204	23.25	0.58
3	Planned	Maing Wah	60	0.85	274	31.26	0.52
4	Planned	Gawlan	120	0.92	594	67.74	0.56
5	Planned	Kengtong	128	0.91	655	74.77	0.58
6	Planned	Dapein 2	140	0.85	769	87.73	0.63
7	Planned	Khankan	140	0.85	642	73.20	0.52
8	Planned	Xo Luu	160	0.89	775	88.41	0.55
9	Planned	Mantaung	225	0.89	992	113.16	0.50
10	Planned	Tongxinqiao	340	0.92	1695	193.36	0.57
11	Planned	Manipour	380	0.91	1903	217.09	0.57
12	Planned	Shweli 2	520	0.92	2814	321.01	0.62
13	Planned	Longdin	570	0.92	2800	319.42	0.56
14	Planned	Yee Nan	1200	0.85	6182	705.22	0.59
15	Planned	Naung Pha	1200	0.90	6650	758.61	0.63
16	Planned	Hutgyi	1360	0.89	7325	835.61	0.61
17	Planned	Kunlong	1400	0.91	7142	814.74	0.58
18	Planned	Wusauk	1800	0.90	10140	1156.74	0.64
19	Planned	Laizar	1900	0.90	10440	1190.97	0.63
20	Planned	Phizaw	2000	0.90	11080	1263.97	0.63
21	Planned	Khaunglanphuu	2700	0.90	14730	1680.36	0.62
22	Planned	Chi Phwae	3400	0.92	17770	2027.15	0.60
23	Planned	Ywathit	4000	0.91	21789	2485.63	0.62
24	Planned	Maingtong	7000	0.90	34717	3960.42	0.57
		Total	**30816**		**162252**		

3.5 A Brief Description of the Essential Features of Storage Type Hydropower Plants

The brief description of essential features of storage type hydropower plants in Myanmar those being (1) Catchment Area, (2) Reservoir, (3) Dam, (4) Spillway, (5) Intake (6) Water conducting system and (7) Powerhouse are discussed in this section.

3.5.1 Catchment Area and Reservoir

Table 3.6 and 3.7 illustrates the project general description of 47 storage type hydropower plants, in which 18 constructed plants, 5 under-construction plants and 24 under-processing plants. The data are generally concerned with the power plants location, reservoir live storage capacity, available drawdown, rainfall and catchment area (Ministry of Electric Power, 2015). Reservoir live storage capacity range from the smallest, 1.23 Mm^3 to the largest, 37881 Mm^3. The multipurpose reservoirs of the constructed power plants located at the large catchment area have larger storage capacity than single purpose projects as shown in Table 3.6. In terms of the planned power plants those will be built on the mainstream of Ayeyarwady and Thanlwin Rivers, their reservoirs have large active storage capacity with the huge catchment area as shown in Table 3.7. The catchment area are ranged from the smallest, 552 Km^2 to the largest, 325000 km^2. The specification of the available drawdown for all storage type hydropower plants are also described in both Tables, those data will be used in predictive equations for the projected EROI calculation in the Chapter 5.

Table 3.6 Project general description of constructed and under-construction hydropower plants (Ministry of Electric Power, 2015).

No.	Projects	Impounds	Location	Reservoir Live Storage Capacity (Mm^3)	Available Drawdown (m) (Full Reservoir Level – Minimum Drawdown Level)		Rainfall (mm)	Catchment Area (Km^2)
1	Kinda	Panlaung River	21° 06 N, 96° 19' E	970.75	207.26	178.49	1060	2239.98
2	Chi Phwae Nge	Chi Phwae Kha River	25°53′40″N 98°8′40″E	1.23	747.67	740.00	2286	552.00
3	Khabaung	Khabaung Creek	18° 49' N, 96° 26' E	1083.61	121.92	97.54	2286	1082.62
4	Kunn Chaung	Kunn Creek	18° 29' N, 96° 26' E	1467.84	161.54	146.30	2540	875.42
5	Kyeeohn Kyeewa	Mone Creek	20° 20' N, 94° 25' E	571.10	113.14	95.40	1143	5073.78
6	Mone	Mone Creek	20° 27' N, 94° 15' E	831.86	158.00	137.16	1143	3802.00
7	Nan Cho	Nan Cho Creek	46' N, 96° 19' E	9.00	304.00	296.00	1651	821.00
8	Paunglaung	Paunglaung River	19° 46' N, 96° 19' E	677.70	190.00	165.00	1207	5082.00
9	Phyuu Chaung	Phyuu Creek	18° 29' N, 96° 26' E	779.56	*	*	2540	1093.00
10	Sedawgyi	Chaungmagyi Creek	22° 19' N, 96° 19' E	448.00	128.00	111.00	840	3424.00
11	Shwegyin	Shwegyin Creek	17° 55' N, 96° 53' E	2078.00	59.00	*	3658	888.00
12	Thaphanseik	Mu River	23° 12' N, 95° 22' E	3552.00	169.00	154.00	1016	9861.00
13	Thaukyaekhat 2	Thaukyaekhat Creek	18° 55' N, 96° 37' E	4440.53	127.00	95.00	2692	2176.00
14	Upper Paunglaung	Paunglaung River	19° 46' N, 96° 19' E	1286.00	370.00	352.00	1524	2572.00
15	Yenwe	Yenwe Creek	18° 04' N, 96° 28' E	1149.00	100.00	70.00	2794	793.00
16	Yeywa	Myitnge River	21° 41' N, 96° 24' E	2607.00	185.00	150.00	838	28204.00
17	Zaungtu	Bago River	17° 45' N, 96° 14' E	407.00	68.00	52.00	2794	850.00
18	Zawgyi 2	Zawgyi River	21° 32' N, 96° 53' E	639.00	648.00	631.00	1411	2111.00
19	Shweli 3	Shweli River	Shan State	5464.00	235.00	195.00	1397	14799.00
20	Upper Kengtaung	Nam Teim Creek	Shan State	128.28	742.00	722.00	1397	5198.00
21	Upper Yeywa	Myitnge River	Shan State	341.00	395.00	385.00	1270	21955.00
22	Thahtay	Thahtay Creek	18° 28' N, 94° 22' E	859.00	*	*	6096	1145.00
23	Middle Paunglaung	Paunglaung River	Nay Pyi Taw & Shan State Border	*	300.00	285.00	1300	4000.00

Remark: Unknown data are described by asterisk (*).

Table 3.7 Project general description of planned hydropower plants (Ministry of Electric Power, 2015 & Myint, 2015a, b).

No.	Projects	Impounds	Location	Reservoir Live Storage Capacity (Mm^3)	Available Drawdown (m) (Full Reservoir Level - Minimum Drawdown Level)		Rainfall (mm)	Catchment Area (Km^2)
1	Wun Tar Pin	Nam Lwae River	Shan State	24.42	667.00	665.00	1245	6262.00
2	Keng Yan	Nam Lwae River	Shan State	22.35	518.00	517.50	1300	15527.00
3	Maing Wah	Nam Lwae River	Shan State	64.94	555.00	552.00	1524	13799.00
4	Gawlan	Naw Chan Kha River	Kachin State	1.36	1510.00	1495.00	3625	740.00
5	Keng Tong	Nam Lwae River	Shan State	32.02	829.00	824.00	1118	4747.45
6	Dapein 2	Dapein River	Kachin State	55.09	179.00	174.00	1524	622.00
7	Khankan	Naw Chan Kha River	Kachin State	2.90	1200.00	1195.00	3348	1416.00
8	Xo Luu	Nam Lwae River	Shan State	630.31	637.00	620.00	1295	7695.00
9	Man Taung	Nam Ma River	Shan State	1214.98	497.13	492.00	1879	3936.78
10	Tongxinqiao	Naw Chan Kha River	Kachin State	5.14	1075.00	1060.00	3268	1743.00
11	Manipour	Manipur River	22° 52' N, 94° 04' E	1554.00	*	*	1651	11549.00
12	Shweli 2	Shweli River	Shan State	82.00	*	*	1778	12364.34
13	Longdin	Naw Chan Kha River	Kachin State	66.90	783.00	768.00	3124	2080.00
14	Yee Nan	Maykha River	Kachin State	1233.48	*	*	2057	11124.00
15	Naung Pha	Than Lwin River	Shan State	812.86	445.00	440.00	1524	141125.00
16	Hutgyi	Than Lwin River	Kayin State	509.06	47.85	40.23	2337	311166.35
17	Kunlong	Than Lwin River	23°31′54″N 98°36′40″E	659.00	519.00	511.00	1879	325000.00
18	Wusauk	Maykha River	Kachin State	3207.05	*	*	2057	18225.75
19	Laizar	Malikha River	26°32′11″N 97°44′34″E	12754.00	375.00	335.00	2057	15562.00
20	Phizaw	Maykha River	Kachin State	5303.96	*	*	2057	16702.83
21	Khaunglanphuu	Maykha River	Kachin State	5303.96	*	*	2057	14654.15
22	Chi Phwae	Maykha River	Kachin State	2332.51	408.00	400.00	2314	20199.32
23	Ywathit	Than Lwin River	20.13 N, 98.60 E	7400.88	219.46	101.96	*	209012.00
24	Maingtong	Than Lwin River	20°27′23″N 98°39′0″E	37881.00	396.54	395.02	1498	183371.00

Remark: Unknown data are described by asterisk (*).

3.5.2 Dams and Spillways

The materials and construction procedures of both gravity dams and fill dams, and spillways which is one of the essential features of the storage type hydropower plants have been discussed in Chapter 2, Section 2.6. Therefore, this section will only focus on different dam types, specification and type of spillways used in the storage type hydropower plants. Table 3.8 illustrates spillways and dams specifications for constructed and under-construction hydropower plants whereas Table 3.9 describes those data of planned power plants (Ministry of Electric Power, 2015 & Myint, 2015a, b).

3.5.2.1 Dams

Both gravity and fill dam are constructed in Myanmar. Gravity dam consists of Conventional Vibrated Concrete (CVC) and Roller Compacted Concrete (RCC). Fill dam consists of Homogeneous Earth-Fill Dam (HEFD), Zone Type Rock-Fill Dam (ZTRFD), Zone Type Earth-Fill Dam (ZTEFD) and Concrete Faced Rock-Fill Dam (CFRD). In addition, one Composite dam is constructed. At the under-processing stage, gravity dam type which are Conventional Vibrated Concrete (CVC) and Roller Compacted Concrete (RCC) and fill dam type which are Zone Type Rock-Fill Dam (ZTRFD), and Concrete Faced Rock-Fill Dam (CFRD) are being planned, whereas Earth-Fill Dams types are not included (Ministry of Electric Power, 2015 & Myint, 2015a,b).

(1). Composite Dam

As shown in Table 3.8, there is only one composite dam type is found in Myanmar, in which composite dam is defined as a dam structure consists of a section of a concrete gravity dam within an embankment dam for spillway section (US Army Corps, 1995). Sedawgyi multipurpose hydropower plant (25 MW) is a composite dam type which is built across the Chaungmagyi. The dam is 41 m height and the total length of the dam is 1256 m with the total volume of 5931150 m^3. The materials composition used in this type of dam is estimated to be soil 40%, rock 30% and CVC 30% (Ministry of Electric Power, 2015).

(2). Gravity Conventional Vibrated Concrete (CVC) Dam

Three gravity dams have been constructed in Myanmar, Chi Phawe Nge (99 MW) on Chi Phwae Kha River, Zawgyi 2 (12 MW) on Zawgyi Creek, and Nan Cho (40 MW) on Nan Cho Creek. Amongst those three dams, Chi Phawe Nge dam is the highest, 220 m, followed by Nan Cho, 51 m and Zawgyi 2, 44 m. In terms of the dam crest length, Zawgyi 2 is the longest with the length of 777 m whereas Chi Phwae Nge, 220 m and Nan Cho, 135 m. In which Zawgyi 2 has the largest dam volume, 3313071 m^3, Chi Phwae Nge, 149163 m^3 and the smallest gravity dam, Nan Cho's dam volume is 88861m^3. Gravity dam is constructed with 100% Conventional Vibrated Concrete (CVC) (Ministry of Electric Power, 2015). There is an under-construction gravity dam, the dam height of Middle Paunglaung (100 MW) on Paunglaung River is 98 m with a length of 515 m. The estimated volume of this dam is about 1097218 m^3. In terms of the planned projects, another 8 Gravity dams will be built namely, Wun Tar Pin (33 MW), Keng Yan (40 MW), Maing Wah (60 MW), Gawlan (120 MW), Dapein 2 (140 MW), Khankan (140 MW), Tongxinqiao (340 MW) and Kunglong (1400 MW) respectively. After those dams are being constructed, there will be altogether 12 gravity dams in Myanmar and the gravity dam types will be the highest number among all dam types. In so doing, Kunglong (1400 MW) will become the highest gravity dam among its dam types because of its height, 103 m. The specifications of gravity dams in terms of dam height, dam crest length and dam volume for the constructed and under-construction dams are shown in Table 3.8. For those planned projects, the dam height and dam crest length are described in Table 3.9. On this account, the river surface widths of the respective planned projects are measured by digital mapping on Google Earth in order to guestimate the dam volumes to calculate EROI values. The sample measurement of river surface width for Gawlan (120 MW) are shown in Figure 3.9 (Myint, 2015c).

Figure 3.9 An example measurement of river surface width on Google Earth by Digital Mapping (Myint, 2015c).

(3). Roller Compacted Concrete (RCC) Dam

The first Roller Compacted Concrete (RCC) dam technology has been used in Yeywa hydropower plant (790 MW) on Myitnge River, the current largest hydropower plant in Myanmar in terms of installed capacity. The dam is 134 m height, the highest among two constructed RCC dam. The dam length is 690 m with a total dam volume of 2854273 m^3. The RCC dam technology has been used a mixture of cement and natural pozzolan, form the natural Pozzolan factory of Poppa, Mandalay region, the central part of Myanmar. The second RCC dam Upper Paunglaung hydropower plant (280 MW) built on Paunglaung River, the dam height is 98 m and 515 m long with the dam volume of 1097218 m^3. The other two RCC dams are at the under construction stage, Upper Yeywa (140 MW) on Myitnge River and Shweli 3 (1040 MW) on Shweli River as shown in Figure 3.10. The dam height of Upper Yeywa is 97 m and the length is 247 m with the estimated dam volume of 365854 m^3. The dam height is 120 m and the length is 1015 m and the total dam volume is estimated as 4134260 m^3. According to the data accessed from MOEP, the materials composition in RCC dam type is estimated to be used RCC 92% and CVC 8% (Ministry of Electric Power, 2015).

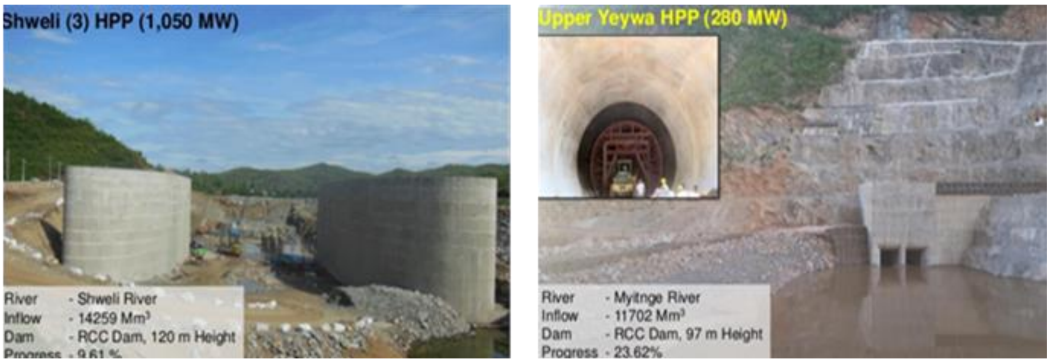


Figure 3.10 Shweli 3 and Upper Yeywa at the under-construction stage (Ministry of Electric Power, 2015).

As the planned projects, Naung Pha (1200 MW), Hutgyi (1360 MW), Chi Phwae (3400 MW), Ywathit (4000 MW) and Maingtong (7000 MW) will be constructed as Roller Compacted Concrete Dam types. The specification such as dam heights and crest lengths, river surface widths for those dams are described in Table 3.9. After those dams being built, Maingtong (7000 MW) dam will be the highest, with the height of 292 m, among 11 RCC dams in Myanmar (Ministry of Electric Power, 2015). Figure 3.11 shows a sample project layout of a planned gravity dam type, Chi Phwae (3400 MW) on Chi Phawae Kha River and Figure 3.12 illustrates the plan view of this plant after being built (Chipwhi, 2012).

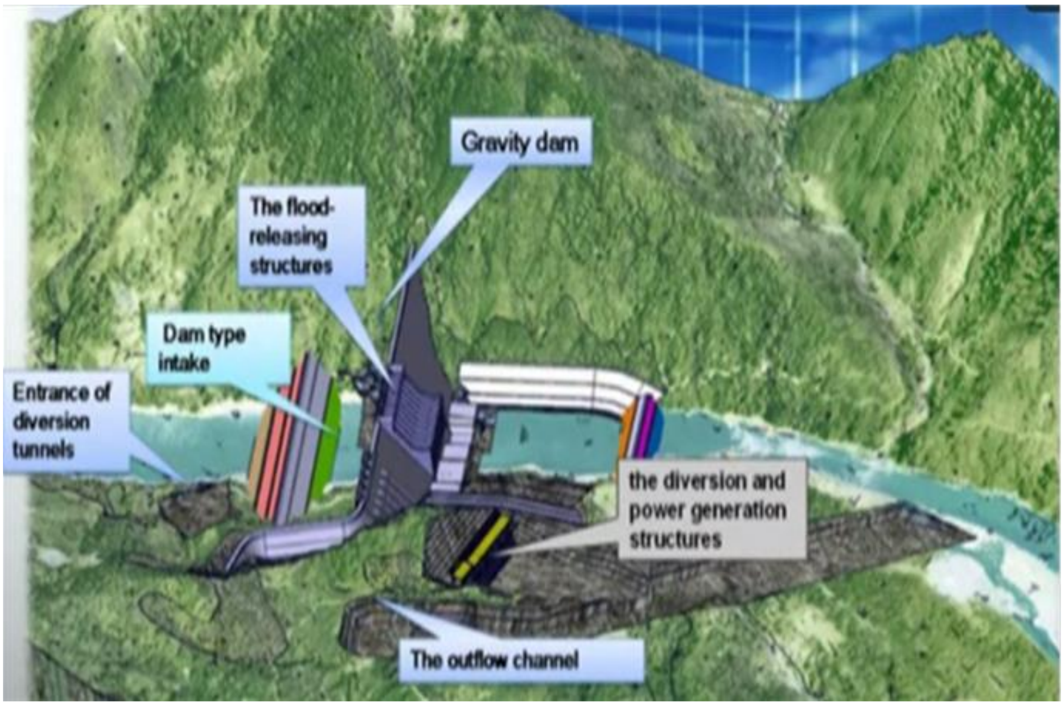


Figure 3.11 Project layout of Chi Phwae hydropower plant (Chipwhi Hydropower Project, 2012).

Figure 3.12 Plan view of Chi Phwae hydropower plant (MW) (Chipwhi Hydropower Project, 2012).

(4). Homogeneous Earth-Fill Dam (HEFD)

Thaphanseik multipurpose hydropower plant (30 MW) on Mu River is the longest dam in Myanmar, with a length of 6884 m. The volume of this massive Homogeneous Earth-Fill dam is 12367122 m^3 which is also the largest dam volume among the current constructed dams. However, the dam is not too high, only 33 m. The other two HERD dams are Zaungtu (20 MW), on Bago River, dam height is 45 m and Khabaung (30 MW) on Khabaung Creek, dam height is 61 m. Zaungtu is the second longest dam among 3 Homogeneous Earth-Fill dam, 1797 m whereas Khabaung dam's length is 280 m. They also occupy a massive dam volume, Zaungtu, 2300000 m^3 and Khabaung 4026661 m^3 respectively. The materials used in the Homogeneous Earth-Fill dam are estimated to be soil 80%, sand 10% and rock 10% (Ministry of Electric Power, 2015). There is no planned project to build Homogeneous Earth-Fill Dam type.

(5). Concrete Faced Rock-Fill Dam (CFRFD)

The only one constructed Concrete Faced Rock-Fill Dam (CFRD) dam type in Myanmar is Thaukyaekhat 2 multipurpose hydropower plant (40 MW) on Thaukyaekhat Creek. The dam is 94 m height and 382 m long. The dam volume is 3822774 m^3, and the materials composition used in this dam is estimated to be Conventional Vibrated Concrete (CVC) 1.8% and Rock 98.2% (Ministry of Electric Power, 2015). As the planned projects, 10 Concrete Faced Rock-Fill Dam will be constructed namely Kengtong (128 MW), Xo Luu (160 MW), Mantaung (225 MW), Shweli 2 (520 MW), Longdin (570 MW), Yee Nan (1200 MW), Wusauk (1800 MW), Laizar (1900 MW), Phizaw (2000 MW) and Khaunglanphuu (2700 MW). Among those power plants, Khaunglanphuu (2700 MW) dam will be the highest dam with a height of 223 m (Ministry of Electric Power, 2015).

(6). Zone Type Earth-Fill Dam (ZTEFD)

A series of Zone Type Earth-Fill dams are constructed on the right tributaries of the Sittaung River, Kunn Chaung (60 MW) on Kunn Creek, Phyuu Chaung (40 MW) on Phyuu Creek, Yenwe (25 MW) on Yenwe Creek. The other one, Mone (75 MW) multipurpose hydropower plant is built on Mone Creek. These types of dams have also massive dam volumes, in which Mone' dam volume is the largest, 10207306 m^3, followed by Yenwe, 5200547 m^3, Phyuu Chaung, 3852991 m^3, and

Kunn Chaung, 2211546 m^3. Amongst those dams, Yenwe dam is the highest, 77 m, and the other dams have also similar dam height, in which Phyuu Chaung 75 m, Kunn Chaung 73 m and Mone 61 m respectively. The materials used for Zone Type Earth-Fill Dam are estimated to be soil 30%, sand 20% and rock 50% (Ministry of Electric Power, 2015). Except these 4 dams, there is no plan to build Zone Type Earth-Fill Dam as the future purposes.

(7). Zone Type Rock-Fill Dam (ZTRFD)

Zone Type Rock-Fill dam types are mostly constructed in Myanmar. Two Zone Type Rock-Fill dams, namely Shwegyin (75 MW) on Shwegyin Creek, and Paunglaung (280 MW) on Paunglaung River as the Sittaung River Hydropower Schemes, Thahtay (111 MW) on Thahtay Creek as one of the Separate River Valley Projects, and Kinda (56 MW) on Panlaung river and Kyeeohn Kyeewa (74 MW) on Mone creek as the Ayeyarwady River Hydropower schemes, and one under-construction plant, Upper Kengtaung (51 MW) on Nam Teim creek which is also as the Ayeyarwady scheme. Amongst those 7 projects, Paunglaung is the highest Zone Type Rock-Fill Dam, 131 m height with the largest dam volume of 11480029 m^3, followed by Thahtay with a height of 91 m, dam volume of 6994261 m^3, Kinda with a dam height of 72 m, dam volume is 4252672 m^3, Upper Kengtaung, with a dam height of 58 m with dam volume of 2814779 m^3, Shwegyin, with a dam height of 56 m, with a dam volume of 8265093 m^3 and Kyeeohn Kyeewa with a dam height of 50 m with a volume of 4737946 m^3 respectively. Shwegyin is the longest Zone Type Rock-Fill dam with a length of 1100 m, followed by Kyeeohn Kyeewa, 1000 m. The dams which have the dam crest length under 1000 m are Paunglaung, 945 m, Kinda 625 m, Thahtay, 618 m and upper kengtaung, 457 m. The materials used in the Zone Type Rock-Fill dam are estimated to be soil 23% as a central core zone, sand 3% and gravel 1% as a filter zone and rock 73% as the shell zone. Manipour hydropower plant (380 MW) will be constructed as Zone Type Rock-Fill dam with a height of 161 m. Dam crest length will be 745 m and the estimated river surface width is 173.5 m (Ministry of Electric Power, 2015). After it is being constructed, it will become the highest Zone Type Rock-Fill dam among its type.

3.5.2.2 Spillway

Most of the hydropower plants in Myanmar used ogee type spillway with either gated or un-gated. Side channel spillway, ski jump type spillway and ladder type spillway are also used. The different types of spillways and their related spillway capacity are described in Table 3.8 and 3.9 (Ministry of Electric Power, 2015). Spillway capacity is defined as maximum discharge from spillway that can be determined by the analysis of design flood, which is the maximum peak flow into the reservoir (Mizuta & Takeda, 2015).

Table 3.8 Spillways and dam specifications for constructed and under-construction hydropower plants (Ministry of Electric Power, 2015).

No.	Projects	Spillway Type	Spillway Capacity (m^3/s)	Dam Height (m)	Dam Crest Length (m)	Dam Volume (m^3)	Type of Dam
1	Sedawgyi	Gated	*	41	1256	5931150	Composite
2	Chi Phawe Nge	Un-gated	*	48	220	149163[1]	Gravity
3	Zawgyi 2	Un-gated	*	44	777	3313071	Gravity
4	Nan Cho	Un-gated	*	51	135	88861	Gravity
5	Upper Yeywa	Gated	5549.00	97	247	365854	Roller Compacted Concrete
6	Upper Paunglaung	Un-gated Ogee	7000.00	98	515	1097218	Roller Compacted Concrete
7	Yeywa	Un-gated Ogee	6600.00	134	690	2854273	Roller Compacted Concrete
8	Shweli 3	Gated	7300.00	120	1015	4134260	Roller Compacted Concrete
9	Zaungtu	Gated	*	45	1797	2300000	Homogeneous Earth-Fill
10	Khabaung	Overflow	65.13	61	280	4026661	Homogeneous Earth-Fill
11	Thapanseik	Gated	5239.00	33	6884	12367122	Homogeneous Earth-Fill
12	Thauk Yae Khat 2	Gated Ogee	6762.00	94	382	3822774	Concrete Faced Rock-Fill
13	Kun Chaung	Ogee	127.43	73	384	2211546	Zone Type Earth-Fill
14	Phyuu Chaung	Ogee	652.70	75	311	3852991	Zone Type Earth-Fill
15	Yenwe	Un-gated Ogee	226.00	77	320	5200547	Zone Type Earth-Fill
16	Mone	Un-gated Ogee	4222.89	61	1317	10207306	Zone Type Earth-Fill
17	Upper Kengtaung	Un-gated Ogee	3171.00	58	457	2814779	Zone Type Rock-Fill
18	Kinda	Gated radial	*	72	625	4252672	Zone Type Rock-Fill
19	Kyeeohn Kyeewa	Gated ogee	4057.80	50	1000	4737946	Zone Type Rock-Fill
20	Thahtay	Gated ogee	9000.00	91	618	6994261	Zone Type Rock-Fill
21	Shwegyin	Gated Ogee	3794.00	56	1100	8265093	Zone Type Rock-Fill
22	Paunglaung	Un-gated Ladder	10001.51	131	945	11480029	Zone Type Rock-Fill
23	Middle Paunglaung	Gated	*	98	515	1097218	Gravity

Table 3.9 Spillways and dams specifications for planned hydropower plants (Ministry of Electric Power, 2015 & Myint, 2015c).

No.	Projects	Spillway Type	Spillway Capacity (m^3/s)	Dam Height (m)	Dam Crest Length (m)	River Surface Width (m)	Dam Type
1	Wun Tar Pin	Gated	*	42.50	177.70	34.33	Gravity
2	Keng Yan	Un-gated	*	28	93	34.00	Gravity
3	Maing Wah	Gated ogee	*	51	237	170.52	Gravity
4	Gawlan	Gated ogee	*	47	119	39.34	Gravity
5	Keng Tong	Gated ski jump	*	54	215	99.94	Concrete Faced Rock-Fill
6	Dapein 2	Gated	*	59	238	110.58	Gravity
7	Khankan	Gated	*	42	234	86.86	Gravity
8	Xo Luu	Gated	*	125	705	75.81	Concrete Faced Rock-Fill
9	Man Taung	Gated	*	109	375	124.48	Concrete Faced Rock-Fill
10	Tongxinqiao	Gated	*	63	145	61.96	Gravity
11	Manipour	Side channel	6965.94	161	745	173.50	Zone Type Rock-Fill
12	Shweli II	Gated radial	5095.33	92	288	54.00	Concrete Faced Rock-Fill
13	Longdin	Gated	*	79	215	94.05	Concrete Faced Rock-Fill
14	Yee Nan	Un-gated	*	159	500	127.00	Concrete Faced Rock-Fill
15	Naung Pha	Gated ogee	*	90	271	156.15	Roller Compacted Concrete
16	Hutgyi	Gated	373.64	118	1127	163.00	Roller Compacted Concrete
17	Kunlong	Overflow	*	103	439	146.00	Gravity
18	Wusauk	Un-gated	*	141	434	165.00	Concrete Faced Rock-Fill
19	Laizar	Un-gated	*	128	481	102.00	Concrete Faced Rock-Fill
20	Phizaw	Un-gated	*	153	312	117.00	Concrete Faced Rock-Fill
21	Khaunglanphuu	Un-gated	*	223	576	128.00	Concrete Faced Rock-Fill
22	Chi Phwae	Gated	24035.51	206	1323	379.00	Roller Compacted Concrete
23	Ywathit	Gated	*	147	1047	216.00	Roller Compacted Concrete
24	Maingtong	Gated	*	292	631	288.00	Roller Compacted Concrete

Remark: Unknown data are described by asterisk (*).

Figure 3.13 (A) Composite Dam (Sedawgyi).

Figure 3.13 (B) Zone Type Earth-Fill Dam (Mone)

Figure 3.13 (C) Roller Compacted Concrete Dam (RCC) (Yeywa).

Figure 3.13 (D) Gravity Dam (Chi Phwae Nge).

Figure 3.13 (E) Concrete Faced Rock-Fill Dam (Thaukyaekhat 2).

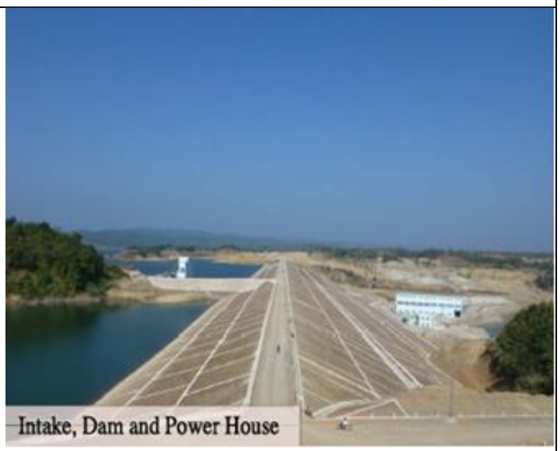


Figure 3.13 (F) Zone Type Rock-Fill Dam (Kyeeohn Kyeewa).

Figure 3.13 Different dam types in Myanmar (Ministry of Electric Power, 2015).

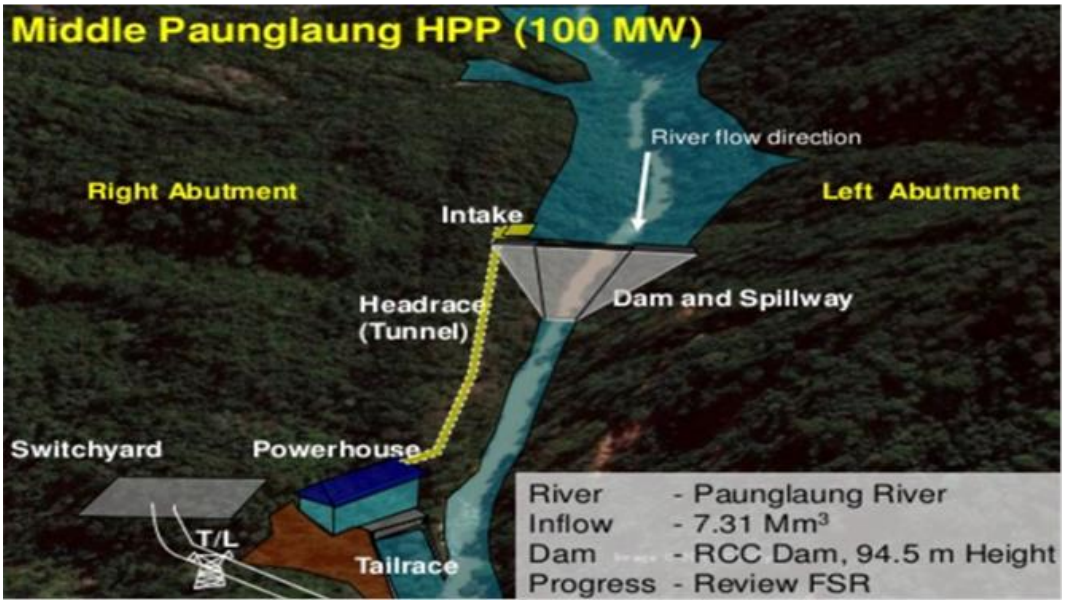


Figure 3.14 The water conducting system of Middle Paunglaung (100 MW) (Massmann, 2015).

3.5.3 Intakes, Water Conducting System and Powerhouse

Table 3.10 and 3.11 illustrate the fundamental data of intake, water conducting system and powerhouse for the storage type hydropower plants. Water conducting system consists of headrace tunnel or channel, surge tank, penstock, tailrace tunnel or channel and tailrace outlet. The headrace tunnel or channel and surge tank are generally used in some power plants in accordance with the necessities of the water conveying system. On this account, 22 out of 47 storage type hydropower plants are installed headrace tunnels and surge tanks. Figure 3.14 shows a sample water conduction system of Middle Paunglaung hydropower plant (100 MW). This under-construction stage power plant is installed 1 headrace tunnel with a length of 700 m which is likely to connect to the surge tank due to the fact that a surge tank is needed to provide if the length of headrace tunnel is longer than 500 m. Then, the surge tank is connected to the penstock as brunching to manifold the two vertical Francis turbines at the above ground type powerhouse. As illustrated in Table 3.10 and 3.11, the length of headrace tunnels range from the shortest, 340 m to the longest, 11240 m according to the topography of the power plants (Ministry of Electric Power, 2015 & Myint, 2015a, b).

Penstock can be a single feeding unit or branching which is defined as bifurcation that generally involves two symmetric pipes for two feeding units or trifurcation (Hydropower Engineering, 2015). One feeding unit of penstock is used in most cases as shown in Table 3.10 and 3.11, bifurcation and trifurcation units are estimated to be installed in some cases (Hydropower Engineering, 2015 & Ministry of Electric Power, 2015).

Three types of powerhouse are built in the hydropower plants of Myanmar namely: surface powerhouse or above ground power house, semi-underground powerhouse and underground powerhouse. Hence, almost all the constructed and under-construction power plants are built above ground type power houses except Paunglaung (280 MW) which is the underground type and Sedawgyi (28 MW) which is semi-under-ground type. In Paunglaung hydropower plant, the under-ground type power house including 37 small and large tunnels that used the sophisticated tunnels technology (Electrical Industry of Burma, 2012). The specification of constructed and under-construction power houses in terms of length, width and height based on their types are shown in Table 3.10. As the under-processing power plants, almost all the power plants are planned to build the above ground type power houses except Maingtong (7000 MW) which is the under-ground type. Table 3.11 describes the specification of power houses for the planned projects in terms of length, width and height based on the power house types (Ministry of Electric Power, 2015 & Myint, 2015a, b).

As the data for intake, and tailrace, just a few data are accessed from the MOEP as shown in Table 3.10 and 3.11. It is found out that both tailrace tunnel and channel type are used in the power plants. No data are accessed concerned with the surge tanks. Table 3.12 describes some work quantities for the under-construction power plants accessed from MOEP. In addition, the weight of the turbines and generators for some power plants are also described in Table 3.13. Most of the data described in this chapter will be used as the fundamental data for the projected EROI calculation in Chapter 5.

Table 3.10 Intake, water conducting system and powerhouse data for constructed and under-construction power plants (Ministry of Electric Power, 2015).

No.	Projects	Intake Tunnel			Headrace Tunnel			Penstock			Powerhouse				Tailrace Tunnel		
		No.	D (m)	L (m)	No.	D (m)	L (m)	No.	D (m)	L (m)	Type	L (m)	W (m)	H (m)	No.	D (m)	L (m)
1	Kinda			*		None		2	3.20	30.48	Above	42	39	53			*
2	Chi Phwae Nge			*	1	3.96	11240.00	1	2.59	1566.00	Above	44	19	32			*
3	Khabaung	1	7.00	45.72	1	6.55	365.76	1	6.60	64.00	Above	38	25	29			*
4	Kun Chaung			*	1	5.48	2282.34	1	4.57	394.72	Above	53	33	29			*
5	Kyeeohn Kyeewa			*		None		1	3.05	260.00	Above	68	37	45			*
								1	5.48	278.58							
6	Mone			*		None		1	*	478.00	Above	79	39	34			*
								3	*	133.00							
7	Nan Cho			*	1	5	2234.00	1	4.00	267.00	Above	42	27	30			*
8	Paunglaung			*		Unknown		4	9.00	80.16	Under-	95	15	43			*
9	Phyuu Chaung			*	1	6	732.00	1	6.00	173.00	Above	40	34	34			*
10	Sedawgyi			*		None		1	3.00	1088.00	Semi-	56	31	39	2	4	46
11	Shwegyin			*		None		2	8.00	736.00	Above	29	77	*			*
12	Thaphanseik			*		None		3	6.00	137.00	Above	61	27	30			*
13	Thaukyaekhat 2			*	1	9	600.00	1	9.00	600.00	Above	66	35	29			*
14	Upper Paunglaung			*		None		2	5.00	149.00	Above	37	40	76			*
15	Yenwe	1	6.00	350		None		1	5.00	155.00	Above	39	25	26			*
16	Shweli 3			*		None		4	7.50	200.00	Above	180	58	70			*
17	Yeywa			*		None		4	7.00	150.00	Above	155	45	60			*
18	Zaungtu			*		None		2	5.00	205.00	Above	46	24	50			*
19	Zawgyi 2			*		None		1	4.00	32.00	Above	108	47	11	1	2	43
20	Thahtay	1	12.80	80		None		1	9.00	148.00	Above			*			*
21	Upper Kengtaung			*	1	8	526.00	3	8.00	115.00	Above	54	29	31			*
22	Middle Paunglaung			*	1	*	700.00	2	4.87	149.35	Above	76.20	40	37			*
23	Upper Yeywa			*	1	12	473.00	2	10.00	212.00	Above	86	40	45			*
					1	12	539.00	2	10.00	238.00							

Remark: Unknown data are described by asterisk (*).

Table 3.11 Intake, water conducting system and powerhouse data for planned power plants (Ministry of Electric Power, 2015 & Myint, 2015a, b).

No.	Projects	Intake Tunnel			Headrace Tunnel			Penstock			Powerhouse				Tailrace Tunnel		
		No.	D (m)	L (m)	No.	D (m)	L (m)	No.	D (m)	L (m)	Type	L (m)	W (m)	H (m)	No.	D (m)	L (m)
1	Wun Tar Pin			*		None		2	*	30.00	Above	47	29	42			*
2	Keng Yan			*		None		2	*	30.00	Above	58	53	58			*
3	Maing Wah			*		None		2	*	30.00	Above	*	*	*			*
4	Gawlan			*	1	5.48	7239.00	1	4	40.00	Above	50	27	46			*
5	Keng Tong			*		None		2	7.31	30.00	Above	74	20	43			*
6	Dapein 2			*		None		2	6.40	150.00	Above	78	42	47			*
7	Khankan			*	1	7.00	5500.00	1	5	300.00	Above	65	18	40			*
8	Xo Luu			*	2	8.53	1018.00	2	*	30.00	Above	73	23	41			*
9	Man Taung	3	10.06	214.58		None		3	8.23	259.69	Above	91	22	48			*
10	Tongxinqiao			*	1	7.60	9700.00	1	5.70	1030.0	Above	73	19	47			*
11	Manipour			*	2	7.80	990.00	4	7.62	93.87	Above	110	37	46			*
12	Shweli 2			*	2	10.67	5011.20	2	*	168.55	Above	113	21	47			*
13	Longdin			*	1	8.00	7610.00	1	6.40	785.00	Above	90	23	46			*
14	Yee Nan			*	2	15.24	850.08	2	*	400.00	Above	*	*	*			*
15	Naung Pha			*		None		3	16.15	375.00	Above	280	33	80			*
								3	13.11	198.00							
16	Hutgyi			*		None		8	*	300.00	Above	424	62	80			*
17	Kunlong			*		None		5	12.00	80.00	Above	245	35	74			*
18	Wusauk			*	2	15.85	710.18	2	*	400.00	Above	*	*	*			*
19	Laizar			*	4	13.11	1038.15	4	*	400.00	Above	*	*	*			*
20	Phizaw			*	2	15.85	340.16	2	*	400.00	Above	*	*	*			*
21	Khaunglanphuu			*	4	10.97	930.00	4	*	400.00	Above	*	*	*			*
22	Chi Phwae			*		None		2	9.60	428.50	Above	248	34	74			*
								3	9.60	349.78							
23	Ywathit			*		None		8	11.28	300.00	Above	362	30	70			*
24	Maingtong			*		None		4	8.53	400.00	Under-Ground	500	45	80			*
								4	10.06	500.00							
								4	10.67	606.00							

Table 3.12 Work quantities for the under-construction Power Plants (Ministry of Electric Power, 2015).

Projects	Work Quantities (m^3)	Dam	Headrace Tunnel	Penstock	Powerhouse	Intake	Spillway	Tailrace Tunnel
Upper Kengtaung (51 MW)	Excavation	362342.37	427584.38	202238.92	45023.79	391621.99	2013044.62	*
	Soil	562955.90	-	-	-	-	-	-
	Rock	2251823.60	-	-	-	-	-	-
	Concrete (RC)	-	19255.00	12969.00	16876.84	1670.69	106896.10	*
Middle Paunglaung (100 MW)	Excavation	570584.46	*	12742.58	371233.86	154694.93	*	*
	Concrete (RCC)	-	-	-	-		-	-
	Concrete (CVC)	511260.67	-	-	-		-	-
	Concrete (RC)	-	10137.43	2605.15	41116.06	7702.18	*	*
Thahtay (111 MW)	Excavation	1218757.08	None	13286.26	116495.51	35000.00	4399305.29	*
	Soil	1398852.22	-	-	-	-	-	-
	Rock	5595408.89	-	-	-	-	-	-
	Concrete (RC)	-	-	15783.81	44174.28	41220.83	156212.72	*
Upper Yeywa (280 MW)	Excavation	682917.39	519874.65	37095.00	304689.27	37435.00	*	*
	Concrete (RCC)	336585.37	-	-	-	-	-	-
	Concrete (CVC)	29268.29	-	-	-	-	-	-
	Concrete (RC)	-	26674.00	31715.00	76172.32	13196.00	*	*
Shweli 3 (1050 MW)	Excavation	1993506.00	None	*	996753.00	227950.62	*	1713169.22
	Concrete (RCC)	3743487.12	-	-	-	109444.61	-	-
	Concrete (CVC)	328475.42	-	-	-	98825.79	-	-
	Concrete (RC)	62297.06	-	37095.07	248338.74	-	*	10000.00

Table 3.13 Weight of turbines and generators (Ministry of Electric Power, 2015).

Projects	Rated Capacity (MW)	One Turbine (kg)	One Generator (kg)
Thaphanseik	10	54900	113500
Khabaung	15	83500	118060
Phyuu Chaung	20	108400	224300
Paunglaung	70	195000	410000

3.6 Conclusions

The developed, under-construction, under-processing and future potential of hydropower resources on the major rivers in Myanmar have been discussed in this chapter, with special attention to the hydropower generation, essential features and fundamental data of storage type hydropower plants those are important fundamental data for EROI calculation. The next chapter, chapter 4 will focus on the application of Carbon Emissions Pinch Analysis (CEPA) technique in the electricity sector to figure out the least carbon emissions reduction scenario based on the different electricity generation mix target proposed in the "National Electricity Master Plan" (2014-2030).

Chapter 4

Electricity Situation Analysis and Minimizing Carbon Emissions in Myanmar through to 2030

4.1 Introduction

Energy is considered a key factor in the socio-economic development of Myanmar as in other countries. It is important to utilize the sustainable energy sources, which can be adapted for economic, environmental, social, and geopolitical dimensions of a country, as the alternatives to non-renewable energy to fulfil the requirement of society's energy needs. Myanmar National Energy Policy is tailored to the needs of these specific goals:

(1) To supply reliable, competitive and affordable energy systems for both energy industries and consumers;

(2) To minimize the impact on the environmental and social situation by applying a geopolitical balance in energy utilization; and,

(3) To formulate energy plans this can use as many renewable energy resources as possible for the environmentally sustainable society.

The basic aim of the Myanmar National Energy Policy is the provision of the majority of sustainable energy in sufficient amounts and on time, which could bring energy security to Myanmar's society (Myanmar National Energy Management Committee, 2014). In so doing, when implementing the country's electricity policy, the National Energy Management Committee (NEMC) addressed the need for the design of electricity policy to be in line with the National Energy Policy to implement the effective utilization of energy resources and policy measures (Japan International Cooperation Agency et al., 2014).

As electricity generation is one of the energy carriers, this secondary energy resource relies heavily on the enrichment of primary energy resources of a country, therefore, the primary energy resources potentials in Myanmar are firstly examined in this chapter. After that, a brief analysis of the country's electricity situation based on the usage of primary energy resources will be discussed. Then, the Carbon Emissions Pinch Analysis (CEPA) technique is used to identify the carbon emissions results regarding three scenarios for different electricity generation mix proposed in the National Electricity Master Plan (2014-2030) (Japan International Cooperation Agency et al., 2014).

4.2 Primary Energy Resources

4.2.1 Primary Energy Resources Potentials

Nature has provided Myanmar with abundant primary energy resources with both renewable and non-renewable energy resources as shown in Table 4.1.

Table 4.1 Primary energy resources potential (Win, 2013).

Primary energy resources potential		
1	Crude Oil (Off shore & On shore) (Proven and Probable)	609.39 MMBBL
2	Natural Gas (Off shore & On shore) (Proven and Probable)	166.13 TSCF
3	Hydro	108,000 MW
4	Coal	711 Million Metric Tons
5	Biomass	Woodfuel – 19.12 Million Cubic Ton
6	Wind	365.1 TWH per year
7	Solar Power	51,973.8 TWH per year
8	Geothermal	93 Locations

Off-shore and on-shore crude oil reserves in Myanmar are 609.39 million barrels (MMBBL) (NEDO, 1997 as cited in Win, 2013). According to 2014 statistics, the crude oil production is totally 19400 barrels per day (bpd), of which 12000 bpd are from off shore and 7400 bpd from on shore. However, current oil production rate is lower than that of other countries. It is anticipated to boost crude oil production in accordance with future demand growth (Myanmar National Energy Management Committee, 2014).

Total proven natural gas reserves are 166.13 trillion TSCF. Furthermore, offshore gas is the most important source of export earnings (NEDO, 1997, as cited in Win, 2013) and Myanmar is ranked 34th globally in terms of natural gas reserves. The total extracted amount of natural gas in 2014 was 1865 mmcfd (a thousand cubic feet of natural gas per day), of which 1100 mmcfd was exported to Thailand, 400 mmcfd exported to China, and the remaining 365 mmcfd was used for the domestic market. In this regard, 60 % of domestic natural gas is distributed to gas fired power plants, 12 % is distributed to fertilizer plants, and the rest is used to produce compressed natural gas (Myanmar National Energy Management Committee, 2014).

In terms of hydropower potential, Myanmar is topographically endowed with abundant hydropower resources from four main river basins: Ayeyarwaddy, Chindwin, Thanlwin, and Sittaung, which are estimated to be capable of producing more than 108,000 MW (NEDO, 1997 as cited in Win, 2013). The detailed discussion of hydropower resources and related issues will be addressed in chapter 5.

Sub-bituminous and lignite coal reserves are estimated at 711 Mt in Myanmar, of which 25 Mt have been utilized (Win, 2013, NEMC, 2014). More than 16 large scale coal deposits have been found along the Ayeyarwady, Chindwin River Basins and the southern part of Myanmar (Yupapin et al., 2011; Win, 2013). Currently, the only coal powered plant in Myanmar is the Tigyit power plant, which uses lignite coal as a fuel. However, due to the poor quality of lignite coal, the power plant produces only 20% of its total installed capacity, 120 MW (Myanmar National Energy Management Committee, 2014).

For biomass energy generation, it can be expected to use 19.12 million cubic ton of wood fuel throughout the whole country. Perhaps a more promising area of new energy generation would be to harness wind energy at the coastal regions in the south, western part and some of the central parts of the country. The wind potential of Myanmar is 365.1 TWh/y (NEDO, 1997 as cited in Win, 2013). The down side of this is that wind potential is relatively low and irregular. Harnessing wind energy is at the very first stage because of its expensive initial cost and the need for technology assistance (Yupapin et al., 2011).

The potential for solar power in Myanmar is 51978.3 TWh/y (NEDO, 1997 as cited in Win, 2013). This resource is abundant, particularly in the dry zone area in the dry season March to May. The average solar radiation is 18 MJ/m^2 - day ($5kWh/m^2/day$). Currently, solar radiation has not been harnessed for mass production due to the technology constraints and high initial installation cost (Yupapin et al., 2011).

Ninety three geothermal sites have been identified, which are located around the igneous belt of Myanmar. A further 43 potential geothermal sites are currently at the investigation stage of taking water samples of hot springs, doing chemical analyses, and performing X-ray investigations to access the potential energy available (Yupapin et al., 2011; Win, 2013).

4.2.2 Primary Energy Consumptions

Myanmar's primary energy supply pattern has been mainly dependent on biomass, crude oil, natural gas, coal, and hydropower over the last 40 years as shown in Figure 4.1.

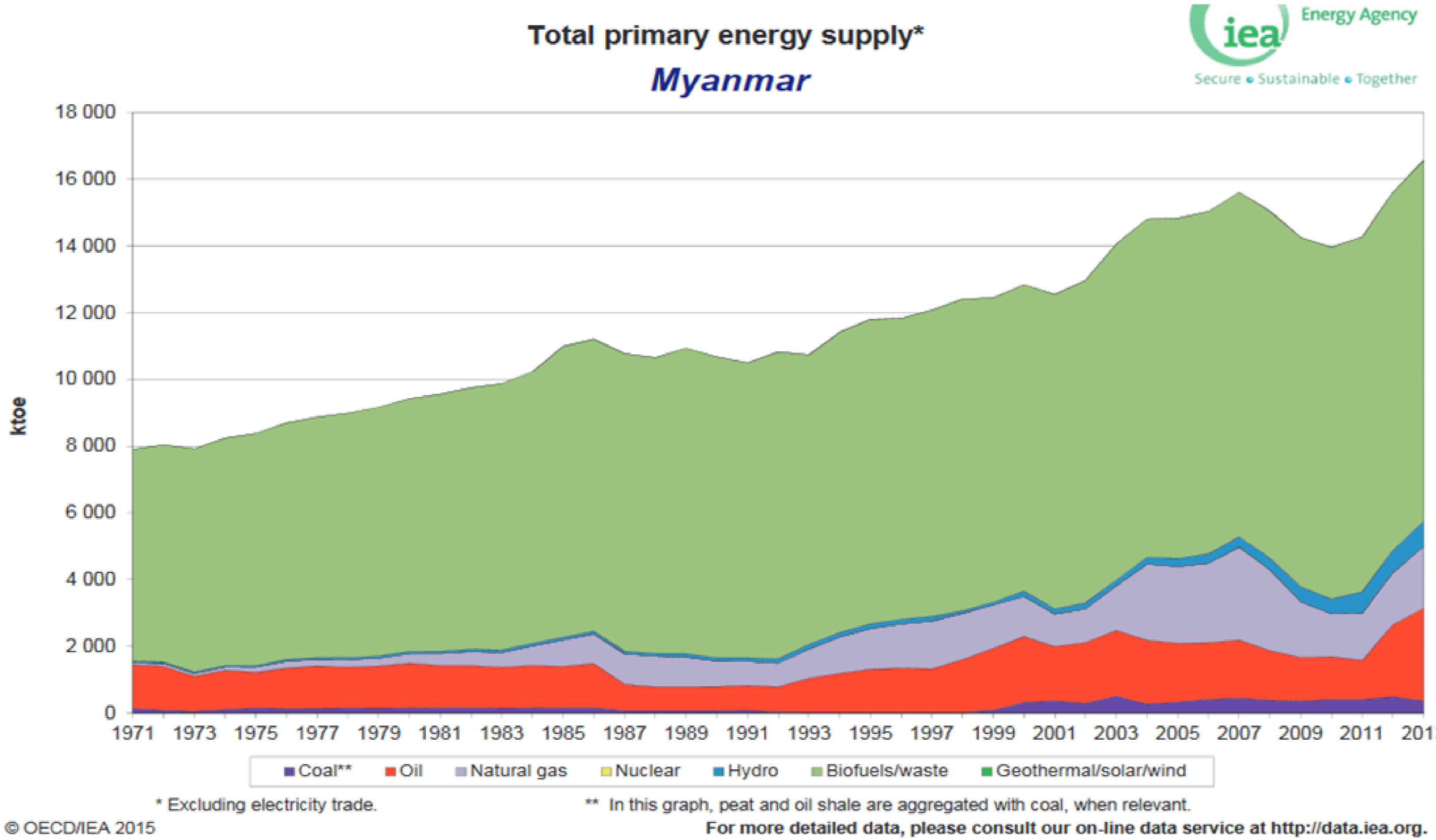
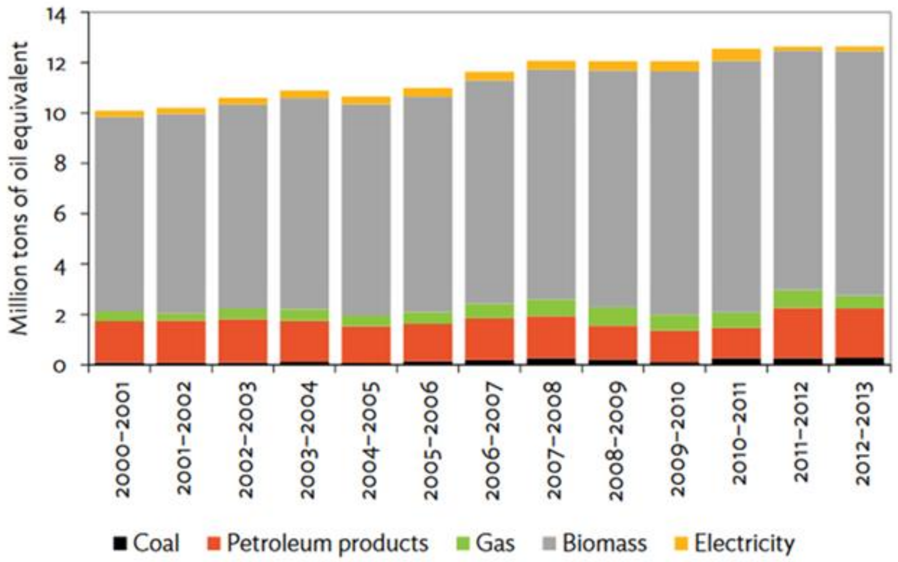


Figure 4.1 Total primary energy supply between 1972 and 2012 (International Energy Agency, 2013).

Most of the primary energy supply came from biomass, which accounted for 75 % of the total primary energy supply. Because of this, in 2008, wood fuel accounted for 75 % of all primary energy consumption that was three times higher than the usage of crude oil and petroleum products. Ninety per cent of the biomass sources were from fuel-wood harvested from natural forests, and this issue has a tendency to cause an environmental degradation problem (Myanmar National Energy Management Committee, 2014). On the other hand, hydropower energy had an upward trend, possibly due to the introduction of medium and large scale hydropower plants. The use of coal and natural gas also increased, but the crude oil supply trend went up and down over the period (International EA, 2015). Figure 4.2 illustrates the total primary energy consumption in Myanmar between 2000 and 2013.

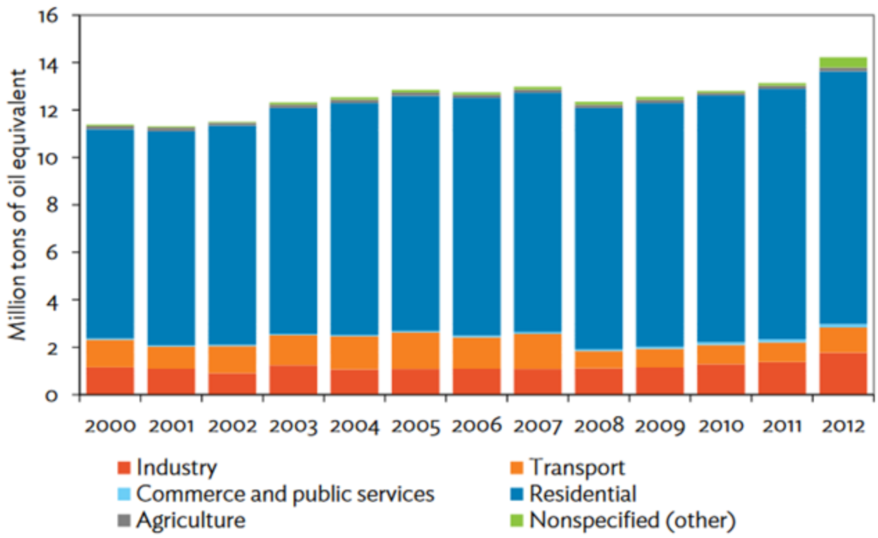


Source: Ministry of Electric Power.

Figure 4.2 Total primary energy consumption from 2000 to 2013 (Nam et al., 2015).

It is evident that overall energy consumption was consistently upwards except there was a drop marginally in 2004-2005. At the beginning of the period 2000, biomass was the largest primary energy consumption, followed by oil and petroleum products, gas, hydro, and coal. This trend was still steady up to 2004 but there was a marginal decrease of energy consumption between 2004 and 2005. However, there was a slight increase in primary energy consumption from 2006 up to 2013 with a significant rise in 2007. Biomass was the main source of energy consumption in the period, followed by petroleum products, gas, electricity, and coal. Coal consumption increased 11% annually whereas natural gas and biomass increased 2.6% and 1.9% respectively (Ministry of Electric Power, as cited in Nam et al., 2015).

Figure 4.3 shows the total primary energy consumption by sectors between 2000 and 2012. Overall, it can be seen that the primary energy consumption by sectors increased until 2007, and dropped down afterward, followed by an upward trend until 2012. It is evident from the chart that the primary energy consumption in the residential sector was far higher than in the other sectors, though the annual average percentage increased 1.6 %. Between 2000 and 2012, the commercial sector grew most, at 8.6 % of annual average, followed by the industrial sector and agricultural sector almost the same at 3.6 % and the transport sector at 0.7% as a whole over the period (Nam et al., 2015).



Source: International Energy Agency database (accessed 28 September 2015).

Figure 4.3 Total primary energy consumption by sector (2000-2012) (International Energy Agency, 2015 as cited in Nam et al., 2015).

4.3 Electricity Situation Analysis

4.3.1 Installed Capacity and Electricity Generation

As shown in Figure 4.4, hydropower has played a significant role in electricity generation in Myanmar over the last 10 years. Natural gas has also been a dominant energy resource since 2000. Furthermore, hydroelectric generation has significantly increased due to the construction of medium and large hydro power plants since 2005. However, no significant new coal fired power plants has been installed since 2000. Moreover, despite there being tremendous wind, solar and geothermal power generation potential, and these technologies are still at the initial stage. Nonetheless, as a reflection of the annual increase in power consumption, the installed capacity has been increased year after year (Nam et al., 2015).

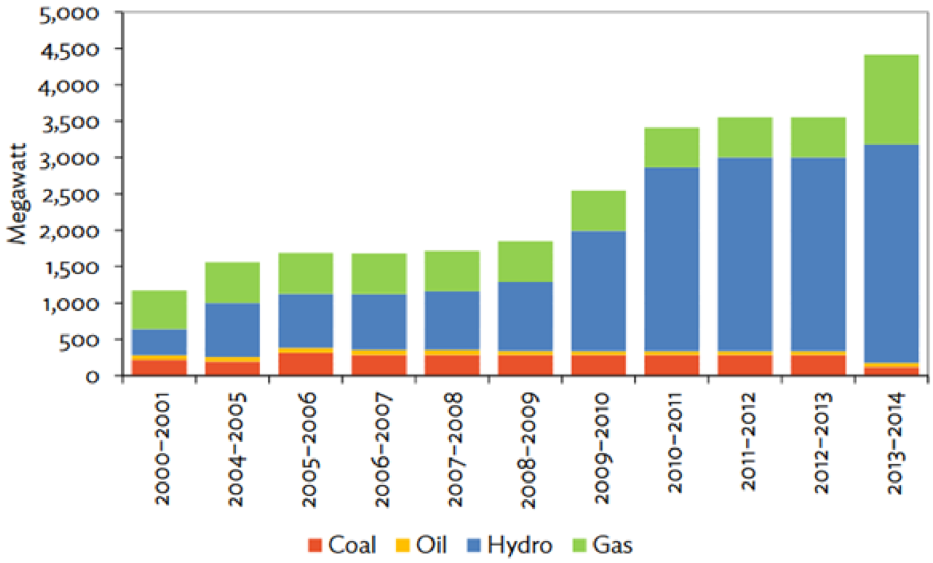


Figure 4.4 Installed capacity by fuel type (2000-2014) (Nam et al., 2015).

The bulk of electricity now comes from medium and large hydropower plants. In 2015, Myanmar's installed capacity generated 4714.61 megawatt (MW) of electricity with hydroelectricity making up over half of this at 68%, including 1% from small hydropower plants, while natural gas accounted for 28%, coal accounted for 3%, and diesel generators accounted for 1 % as shown in Table 4.2 (Ministry of Electric Power, 2015).

Table 4.2 Installed Capacity (MW) in Myanmar by 2015 (Ministry of Electric Power, 2015).

No.	Power plants	No. of plants	Installed capacity (MW)	Percentage (%)
1	Hydropower plants	25	3151.00	67%
2	Small hydropower plants	32	34.17	1%
3	Coal fired power plant	1	120.00	3%
4	Natural gas power plants	18	1329.33	28%
5	Diesel generators	564	80.109	1%
	Total	**640**	**4714.61**	**100%**

The electricity sector in Myanmar used both renewable and non-renewable energy sources – hydropower, natural gas, oil, and coal – over the last 40 years as illustrated in Figure 4.5.

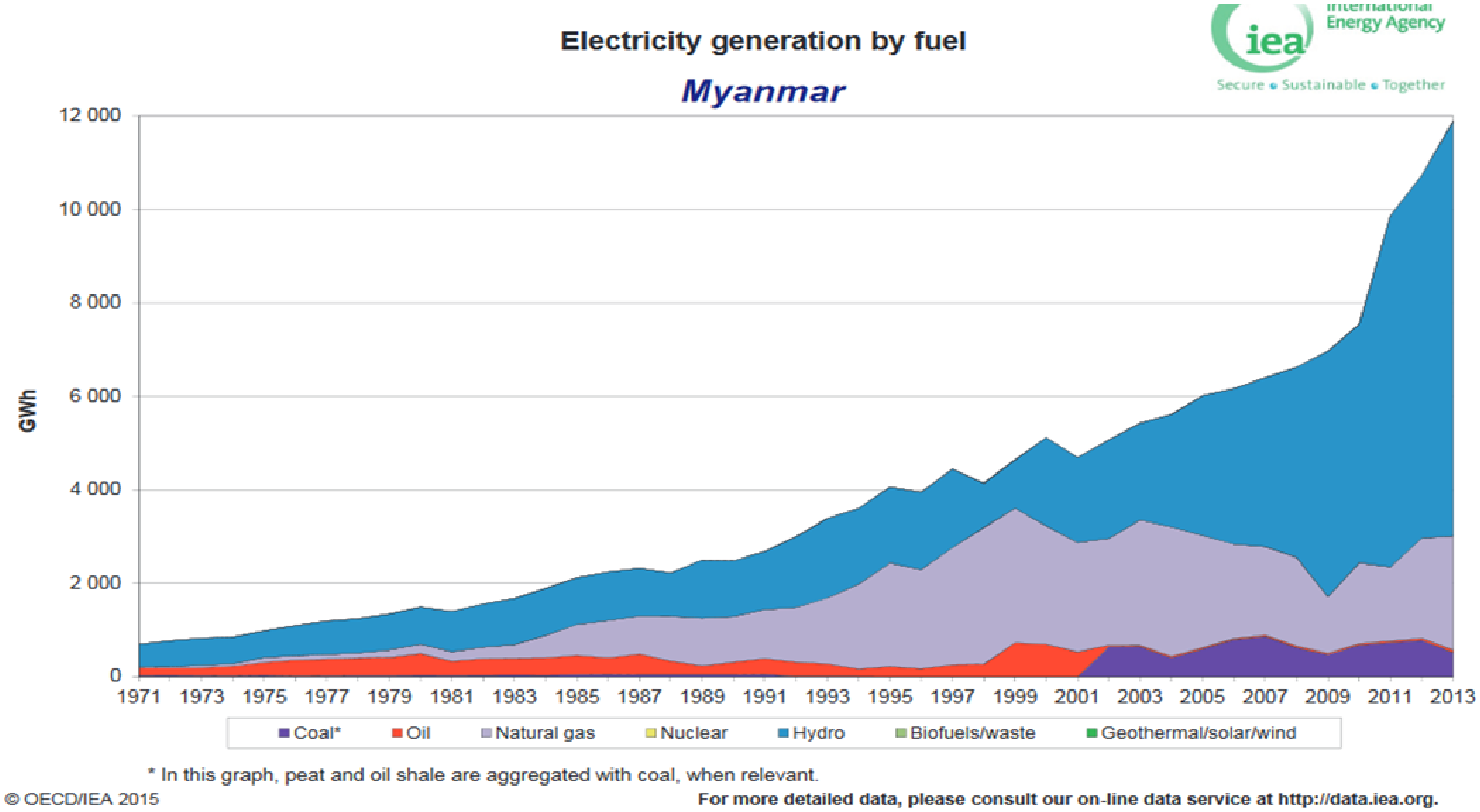


Figure 4.5 Electricity generation by fuel from 1972 to 2031 (International Energy Agency, 2013).

Of these, hydropower has been the dominant energy resource since 1998. Furthermore, oil generation went up and down between 1972 and the late 2000s, but the usage of oil has fallen marginally since 2000. In the same period, coal has experienced an increase trend for electricity generation. On the whole, the power system has heavily relied on hydropower over the last four decades and it was the highest in 2012, with 70% of the total resources. Therefore, the majority of electricity generation is from renewable sources, making Myanmar one of the lowest carbon dioxide emitting countries in terms of electricity generation.

4.3.2 Electricity Consumption

In terms of electricity consumption, the power demand in Myanmar recorded an annual increase rate by several per cent during the 2000s as shown in Figure 4.6. However, from 2010 rapid development and investment progressed concurrently with transition to democratization evolution. As a result, power consumption also showed a sharp increase with a growth of 26.5% from 2009 to 2010, 21.9% from 2010 to 2011, and 7.2% in 2012. In this regard, industrial, commercial consumption and consumption for general purposes accounted for most of the electricity consumption (Japan International Cooperation Agency, et al., 2014). In 2013, Myanmar consumed a total of 19875 GWh of electricity, of which, hydropower accounted for 13871.8 GWh, gas accounted for 5403 GWh and coal accounted for 600 GWh respectively (Myanmar National Energy Management Committee, 2014).

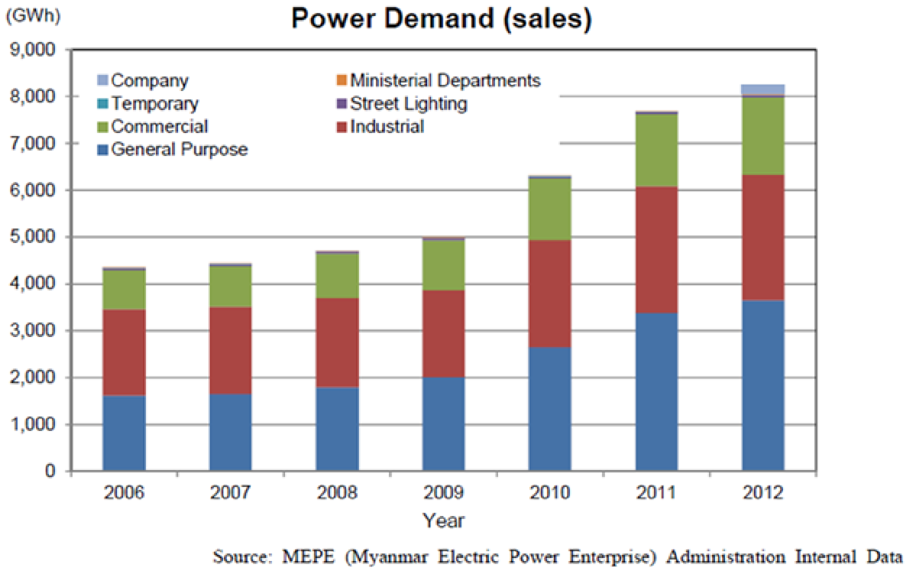


Figure 4.6 Electricity consumption 2006-2012 (Japan International Cooperation Agency et al., 2014).

4.3.3 Organization

Myanmar's electricity sector can be divided into four different parts:

Generation – The electricity generated from medium and large hydropower plants, natural gas power plants and coal fired power plants is injected into the grid connected transmission lines. This generated electricity is transmitted via high voltage power lines to the major cities of the country. For remote regions of the country, the generation medium is small hydropower plants and isolated diesel generators (Myanmar National Energy Management Committee, 2014).

Transmission – The Ministry of Electric Power operates the national transmission network, consisting of 10057.09 km of high voltage lines interconnecting generating power stations with grid exit points to supply distribution networks. The current transmission system consists of an interconnected overhead grid of 230 KV, 132 KV and 66 KV, 250 lines with a total of 10057.09 km covering some parts of the country (Aye, 2013, Nam et al., 2015). As power is transmitted over long distances, the 230 KV transmission systems suffers from high voltage drop, in some cases up to 10 %, although transmission lines are still in good condition (Asian Development Bank, 2012; Nam et al., 2015). During the six years period from 2007 to 2013, the overall average transmission loss was 6.7% resulting in unavoidable total energy losses of almost 4000 GWh. Currently, plans exist to introduce the 500 kV, two transmission lines with a total length of 423.26 km, 230 KV, 18 transmission lines with a total length of 2392 km, 66 KV and 38 transmission lines with a total length of 2197 km, so totally 5011 km will connect the majority of the country's generation facility. The on-going under construction transmission lines are shown in Table 3.4 (Ministry of Electric Power, 2015).

Distribution – The distribution system is comprised of a network of 33 kV, 11 kV, and 6.6 kV lines originating from the grid and zone substations. These lines are connected to the distribution transformers, which then supply single and three phase 400/230 volt lines to connected customers. The 33 kV system is used to connect 33/11 kV zone substations. This could possibly be used to directly supply 33/0.4 kV distribution transformers in the future. The construction of the system is generally an overhead system, but some distribution in the populated areas is per underground system. Some distribution systems need to be modernized so as to avoid distribution losses. Although the distribution losses have decreased over the last five years, the distribution network still needs upgrading to avoid unnecessary losses. In regard to this, there are plans to upgrade several 6.6 kV systems to 11 kV, and expand the 33 kV network by 400 km, the 11 kV network by 360 km, and the 6.6 kV network by 250 km. The existing transmission and distribution lines are shown in table (Sharma 2013, as cited in Nam et al., 2015).

Regulation – The Ministry of Electric Power is responsible for management of the electricity industry and the electricity system in real time to ensure that generation matches demand. The Myanmar Electric Power Enterprise (MEPE) is one of the governmental organizations under the Ministry of Electric Power responsible for implementing electricity policy and measures for the whole country in compliance with National Energy Policy. MEPE is leading other key stakeholders in the energy and electricity sector such as Ministry of Energy (MOE), Ministry of Science and Technology (MOST), Ministry of Agriculture and Irrigation (MOAI), Ministry of Industry (MOI), Ministry of Livestock, Fisheries and Rural Development (MLFRD) and Ministry of Mining (MOM) and closely collaborates with Ministry of Electric Power to improve the electricity sector in the country as a whole (Japan International Cooperation Agency, et al., 2014).

Table 4.3 Existing transmission lines (Nam et al., 2015).

Voltage (kV)	Number of Lines	Length (km)
230	47	3139.86
132	40	2263.04
66	163	4602.19
Total	**250**	**10057.09**

Table 4.4 Under construction transmission lines (Ministry of Electric Power, 2015 as cited in Nam et al., 2015).

Voltage (kV)	Number of Lines	Length (km)
66	38	2197.00
230	18	2392.00
500	2	423.26
Total	**58**	**5011.00**

Table 4.5 Existing distribution lines and substations (Nam et al., 2015).

Voltage (kV)	Length (m)	Capacity (MVA)
33	7311.48	4630.55
11	15016.08	5079.79
6.6	1349.97	1503.17
0.4	20773.85	Unknown
Total	**44451.39**	**11213.51**

4.3.4 Electricity Generation Planning for Myanmar through to 2030

Per capita electricity consumption in Myanmar is the lowest among Southeast Asia countries at 180 kWh per capita in 2014 despite it being rich in both renewable and non-renewable resources for electricity generation (Myanmar National Energy Management Committee, 2014). Otherwise, according to 2014 power sector data, 35 % of Myanmar people can access electricity, reflecting the lack of electricity infrastructure throughout the country. This percentage results from the statistics on 23,034 villages electrified, from the total inhabited villages, 64,917 (Ministry of Livestock, Fisheries and Rural Development, 2014). It has now become evident that the next challenge facing the Myanmar Government is to make electricity available to 100 % of the country’s population, so as to promote the socio-economic development of the people.

As electricity is one of the basic infrastructures for the development of the country’s economy, the government must take into consideration the electricity needs for not only the local industrial zones and the special economic zones, but also even the small and medium enterprise for future generation purposes (Khaing, 2015b). Likewise, when the electricity generation to meet future demand is being considered, it is impossible to leave out the projected population in the future. Therefore, the demand for electricity generation will significantly increase in the future along with a growing population. By 2020, Myanmar's population is expected to grow from the 2014 level of 51 million to 56 million and the projected population in 2030 will be 59 million (Myanmar Ministry of Labour, Immigration and Population, 2014).

For these reasons, coupled with the expected moderate economic growth, installed capacity will need more than eight times as much electricity in 2030 as was required in 2014. Because of this situation, MOEP has been implementing "The National Electricity Master Plan" (2014-2030) in close collaboration with the Japan International Cooperation Agency (JICA), NEW Japan Engineering Consultant Inc. and the Kansai Electric Power Co. Inc. to efficiently implement the future generation target. In this regard, key measures have been proposed to the government, including taking into account carbon emissions reduction, investigating the adoption of Clean Coal Technology (CCT) and introducing the technology of Ultra Supercritical Plant (USC) in Myanmar (Japan International Cooperation Agency et al., 2014).

With the assistance of JICA et al., numerous scenarios have been commissioned to provide insights into how Myanmar can choose mainstream power plant types to avoid serious adverse effects including environmental impacts, social impacts and the necessity for the resettlement of the indigenous people. Ecosystems, rare species, water pollution, air pollution and greenhouse gas emissions are also being considered, based on the lessons learned from previous situations to identify the future electricity plan for Myanmar (Japan International Cooperation Agency et al., 2014).

Based on generating ideas from the macro analysis done by JICA et al., and MOEP, it is stated that the future electricity demand in Myanmar will be at a standard around minimum 3862 MW to a maximum 4531 MW in 2020 and a minimum 9100 MW to maximum 14542 MW by 2030 (Japan International Cooperation Agency et al., 2014, Khaing, 2015b). Table 4.6 illustrates the comparison of electricity demand in three different years in terms of high case and low case (including both for industry and non-industry).

Table 4.6 Results of demand forecast by 2012, 2020 and 2030 (Khaing, 2015b).

Year	High Case (MW)			Low Case (MW)		
	Total	Non-industry	Industry	Total	Non-industry	Industry
2012	1874	1265	609	1874	1265	609
2020	4531	3060	1472	3862	2390	1472
2030	14542	9819	4723	9100	5361	3468

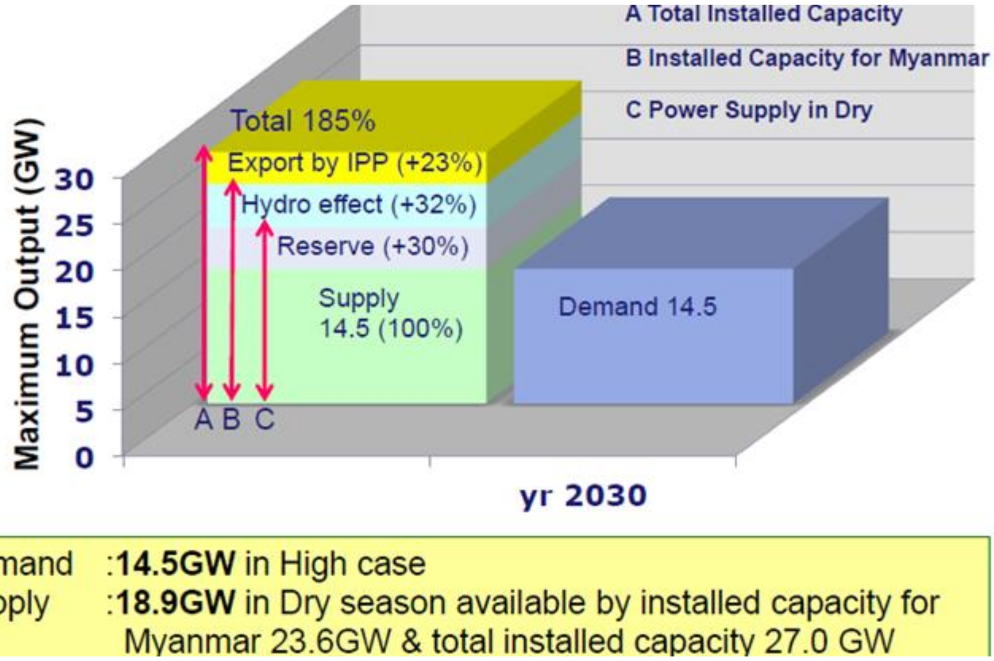


Figure 4.7 Electricity demand and supply (Khaing, 2015a,b).

This study focuses on the high case. From the demand side, although the installed capacity needed is calculated 14542 MW (14.54 GW) by 2030 in terms of high case, it is needed to take into account other factors in the supply side, such as the hydropower fluctuation in dry season, hydropower effects and future export availability as shown in Figure 4.7. Therefore, the installed capacity for the supply side is calculated as follows:

(a) Capacity based on the basic demand = 14.54 GW

(b) Capacity for the basic demand including reserve = 18.85 GW

14.54 GW + reserve (30% of basic demand)

(c) Capacity for the basic demand, reserve purposes including hydropower effect:

18.85 GW + hydro effect (32% of basic demand) = 23.49 GW

(d) Capacity for the basic demand, reserve purposes, hydropower effect and future export availability:

23.49 GW + export (23 % of basic demand) = 26. 84 GW

(~ 27 GW) (Khaing 2015a, b)

It is clear from the above calculations that the future electricity demand would be a minimum amount of 23.49 GW excluding export availability, and the maximum amount if export requirements are taken into account would be of 27 GW. Therefore, three scenarios have been proposed to meet future demand and supply targets of Myanmar in 2030, in which the generation mix targets for all scenarios are mainly based on the tremendous resources of hydropower generation (Japan International Cooperation Agency et al., 2014).

4.4 Myanmar Electricity Demand Growth Analysis

The electricity sector in Myanmar has experienced consistent growth in demand since 1990 and a corresponding increase in net emissions as illustrated in Figure 4.8.

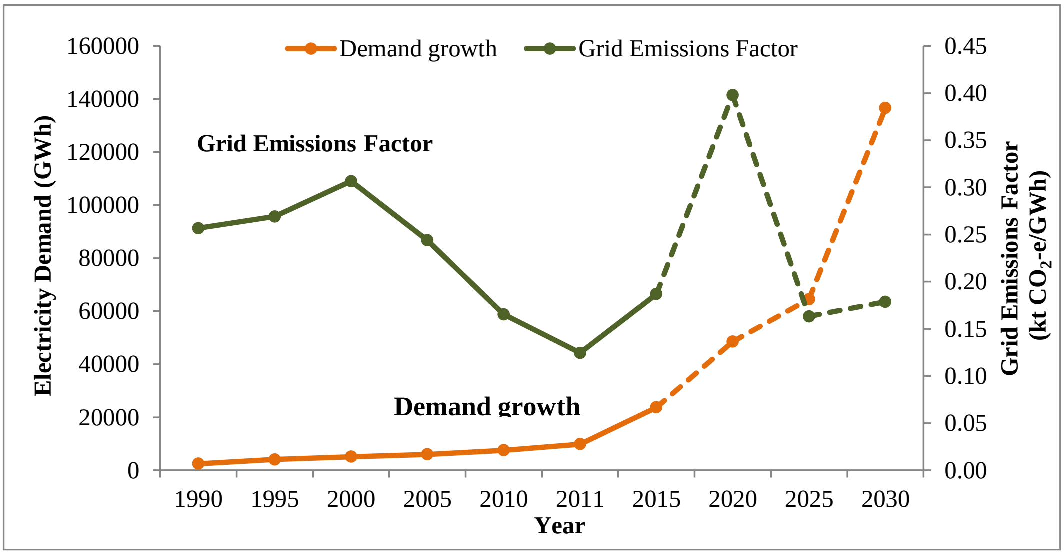


Figure 4.8: Projected electricity demand growth in Myanmar through to 2030. Data from Ministry of Electric Power, 2015 and Walmsley et al., 2015a.

As Myanmar has seen acceleration of a series of reform processes in the political, economic and social sectors since 2011, electricity demand has significantly increased in line with economic reforms (Myanmar National Energy Management Committee, 2014). The average yearly growth in electricity demand between 2009 and 2014 was 15%, whereas the future demand growth from 2014 to 2030 is estimated at 13 % on kWh basis (Japan International Cooperation Agency et al., 2014), reflecting an increasing trend to higher Grid Emissions Factor (GEF).

Three scenarios for projected power demand in 2030 are illustrated in Figure 4.9. Scenario 1 is defined as “Domestic Energy Consumption”. This clear concept is formulated based on large hydropower resources and the intention to maximize the utilization of domestic energy by constructing possible hydropower plants and gas powered plants throughout the country. Scenario 2 is named as "Least Cost", in which this concept is clarified with the aim of constructing possible hydropower plants and reducing gas powered plants after 2016. The utilization of hydropower and other renewable resources (solar, wind, biomass and geothermal) in this scenario remains almost the same as in scenario 1. However, the purpose of this scenario is to reduce the number of gas power plants after 2016 and substitute coal fired power plants. Scenarios 1 and 2 are based on the calculation of a 13% per year increase in electricity demand, to meet the basic demand of Myanmar in 2030, in which the power demand will be 14.5 GW and reserve 30%, and hydropower effect 32 % of the basic demand plus future export availability 23 % of the basic demand, totally about 28 GW (Japan International Cooperation Agency et al., 2014).

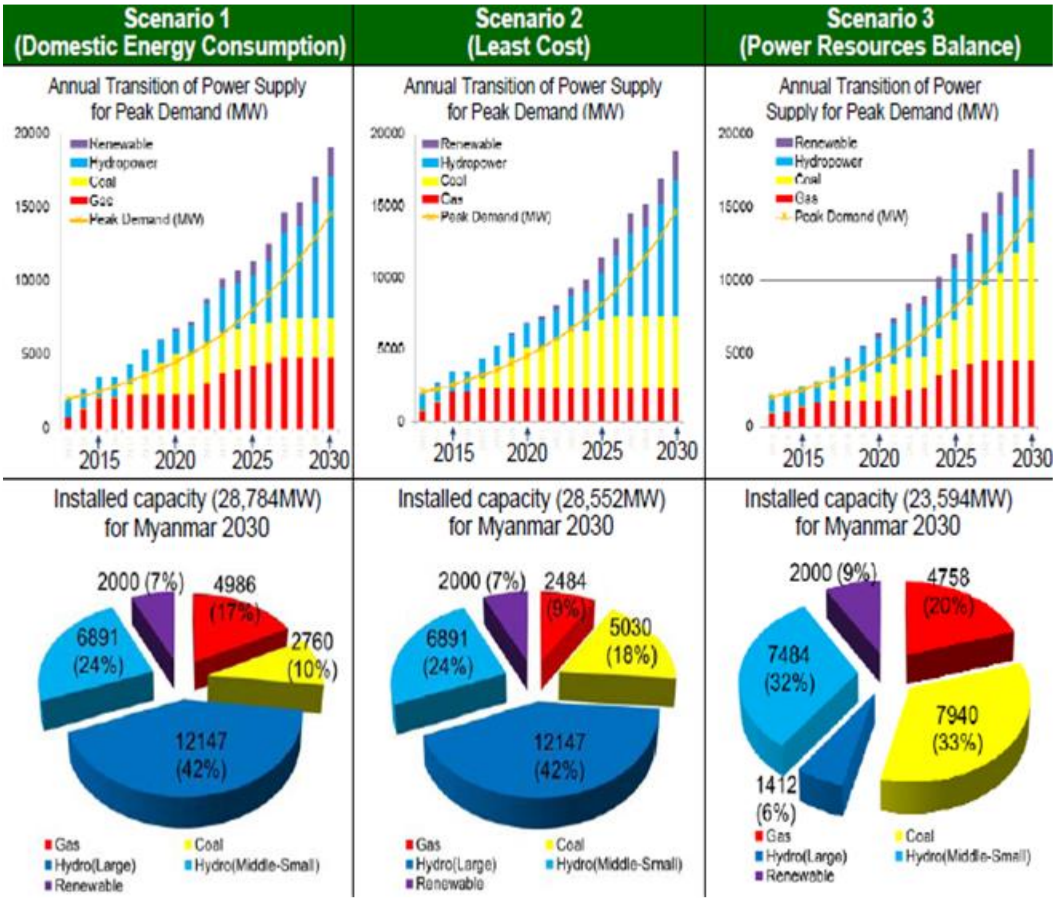


Figure 4.9 Installed capacity and power supply for different scenarios (Japan International Cooperation Agency et al., 2014).

Scenario 3 is defined as “Power Resources Balance” which is formulated by considering the best harmonization of the country’s power resources. In scenario 3, a 13 % per year increase in demand, 14.5 GW basic need, plus reserve 30 % and hydropower affect 32 % of the basic need, totally about 24 GW, which does not include export purposes. In this regard, the installed capacity of hydropower plants with high feasibilities will be 8.89 GW, which is less than half of the 19.03 GW estimated in scenarios 1 and 2 (Japan International Cooperation Agency et al., 2014). For this study, the case for scenario 2 is considered in terms of two different options, (as option I and option II) for the evaluation of the best possible generation mix target in order to reduce carbon emissions in 2030. Therefore, scenario 2 is regarded as the best fit plan for the effective utilization of the country’s primary energy resources (Khaing, 2015a, b). Scenarios 1 and 3 will also be analysed to evaluate the emissions situations resulting from different energy generation mix targets.

As Myanmar is a party to the United Nations Framework Convention on Climate Change (UNFCCC), and a member of non-Annex 1 Developing Countries (United Nations Framework Convention on Climate Change, 2014), the government has a strong desire to reduce overall emissions, and as a result this study identifies that the scenario 2 (option II) can reduce overall emissions by up to 5113 kt CO_2-e in 2030 by optimizing the best renewable generation mix target. A total electricity generation target of 136605 GWh (28 GW) for 2030 is set to meet predicted future demand which is driven by the projected population and moderate economic growth. It is noted that Myanmar’s population is predicted to peak in 2030 at 59 million and therefore, 136605 GWh (28 GW) total electricity generation target for 2030 may also be the peak.

4.5 Applying Carbon Emissions Pinch Analysis (CEPA) Techniques in Different Scenarios

As stated previously, Carbon Emissions Pinch Analysis (CEPA) is useful for examining the impact of electricity generation in terms of carbon footprint for both individual plants, resources and for the sector as a whole (Walmsley et al., 2014). Moreover, the theory and methods of CEPA, based on the composite curves explanation have been described in Chapter 2 in Section 2.2. Therefore, the following discussions will only focus on the application of CEPA technique for planning how Myanmar can best fulfil future electricity demand for a population that is anticipated to peak in 2030, while also fulfilling the goal of lowest emissions as possible from renewable generation, and lower environmental carbon footprint. Energy generation methods are analysed through spread sheet optimization to determine the 2030 generation mix that meets the future electricity demand. For this study, the emissions comparison from the three scenarios 1, 2 and 3 will be examined first. After that, the scenario 2 is considered based on option I and option II, such that electricity demand and supply will be fulfilled by using the "least cost" approach, which utilizes the most renewable resources. The comparison of carbon emissions reduction for the two options will illustrate which option is the best fit to gain carbon emissions reduction.

In the calculation of emission comparison for three scenarios, the generation mix ratio for each scenario will be figured out from Figure 4.9. To calculate the annual energy (TWh) from the plants' installed capacity (GW) for all resources, the values of capacity factor for hydropower, coal and gas are referenced from the National Electricity Master Plan, 50%, 70% and 75 % respectively (Japan International Cooperation Agency et al., 2014). The capacity factor for renewables (solar, wind, biomass and geothermal) is estimated as 34 % (U.S Energy Information Administration, 2011). The emissions factor for all renewable resources including large hydropower plants are assumed as 0 kt CO_2-e/GWh; for natural gas is 0.422 kt CO_2-e/GWh, and for coal is 0.733 kt-CO_2-e/GWh respectively (Ministry of Economic Development, 2013 as cited in Walmsley et al., 2014).

4.6 Results and Discussions

4.6.1 Carbon Emissions Pinch Analysis for Different Scenarios

Using the CEPA composite curve method, the electricity generation mixes in Myanmar by 2030 based upon the three scenarios are illustrated in Figure 4.10. The demand profile for each scenario is clearly unique and reflects the needed tremendous energy resources, renewable and non-renewable.

A large portion of the generation in scenarios 1 and 2 is comprised of hydropower based generation, whereas scenario 3 has a much higher share of fossil resources, especially coal. Hydropower resources in scenario 3 are half for scenarios 1 and 2. Renewables such as solar, wind, biomass and geothermal contribution in the three scenarios are exactly the same. However, it is clearly demonstrated that scenarios 1 and 2 have lower carbon emissions than scenario 3 due to the high utilization of hydropower resources and harmonization of fossil usage, coal and gas. The emissions result for scenario 1 is the lowest at 26247 kt CO_2-e, Scenario 2 is the second lowest at 29516 kt CO_2-e, and scenario 3 is the highest, 48913 kt CO_2-e due to the fossil fuel oriented generation mix target. As a result, the carbon emissions reduction is controlled by the proportion of fossil fuel and non-fossil fuels contribution percentage in the generation target. Furthermore, even though the total power generation amount of scenario 3 is almost 24 GW, lower than for scenario 1 and 2 which are above 28 GW, the result of the emissions amount is significantly higher in scenario 3 than the two others.

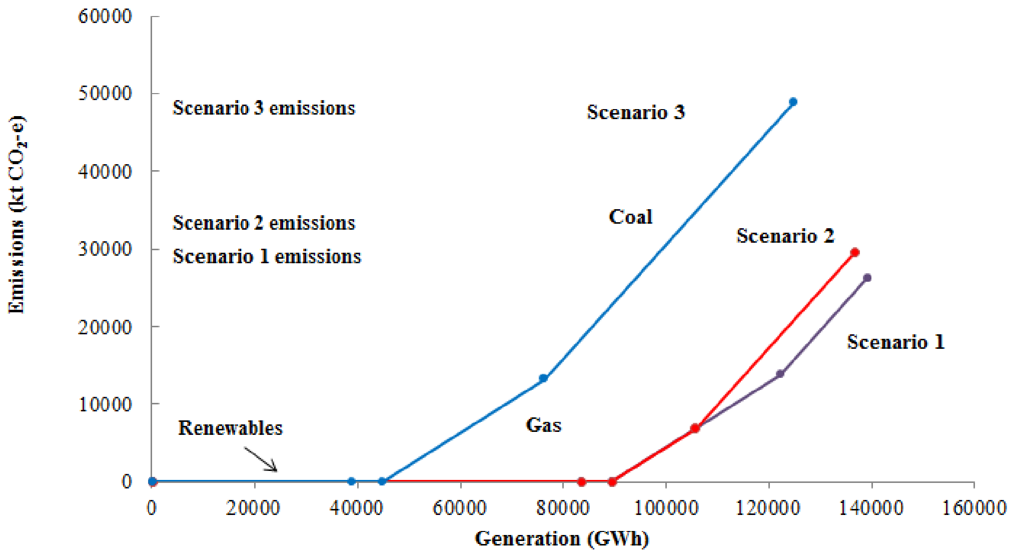


Figure 4.10 Comparisons of carbon emissions and electricity generation in Myanmar by 2030 based on three scenarios (Data from Japan International Cooperation Agency et al., 2014; Ministry of Electric Power, 2015; Walmsley et al., 2014).

4.6.2 Carbon Emissions Pinch Analysis for the Best Possible Option Based on Scenario 2 through to 2030

The CEPA composite curve method will be used again to figure out the best option of electricity generation mix target which can support the lowest carbon emissions in Myanmar by year 2030 based upon scenario 2. Figure 4.11 illustrates the possible option I and option II for the demand and supply electricity generation mix target for the years 2013, 2020 and 2030 (Japan International

Cooperation Agency et al., 2014). For year 2030, both options are based on the scenario 2 generation mix target. There has been a significant shift in the generation mix between the years 2013, 2020 and 2030. Although the generation mix is still dominated by hydro, the amount of coal resources is significantly higher in 2020 and 2030 than in 2013. Furthermore, coal generation has been increased twenty three times higher in 2020 than in 2013 for both options. Also, the coal amount is roughly doubled in option I of 2030 at 5.03 GW, whereas for option II of 2030 it is 2.35 GW. Natural gas generation has been increased four times in 2020 for both options from 2013, and then again roughly the same in 2030. Renewables (solar, wind, biomass and geothermal) generation is also added to the generation mix starting in 2020, although it is still only a relatively small portion of the total (2 % in 2020 and 7 % in 2030 for both options).

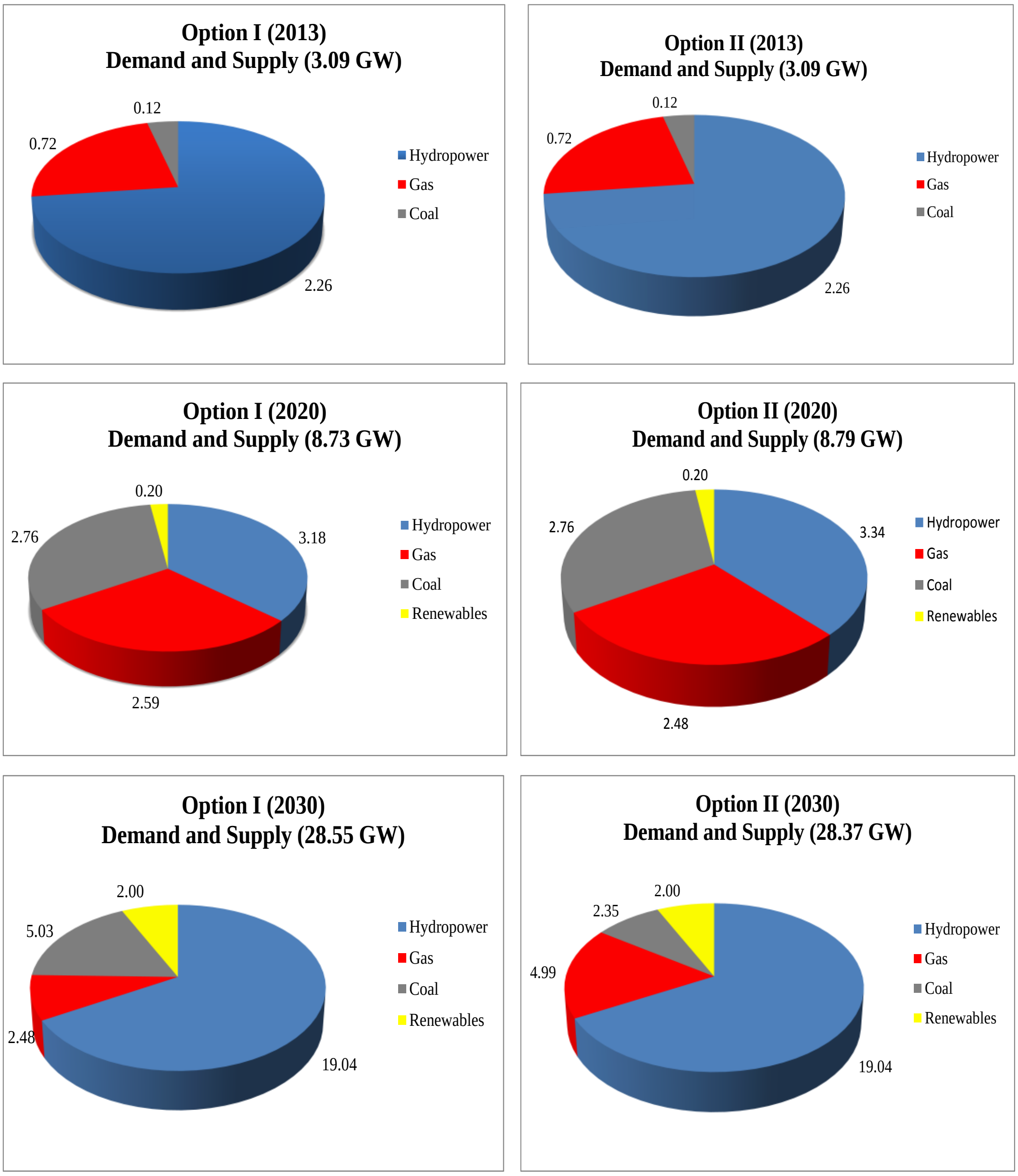


Figure 4.11 Power demand and supply for the year 2013, 2020 and 2030 based on scenario 2 (Japan International Cooperation Agency et al., 2014).

Based on the option I and option II, the analysis will figure out which option can best provide the generation mix target through to 2030, by resulting in the lowest possible carbon emissions. Figure 4.12 illustrates the results of the demand and supply profiles coupled with carbon emissions for the years 2013, 2020 and 2030 by using the CEPA analytical tool. It can be seen that the total electricity demand and carbon emissions in 2013 for option 1 and 2 are the same, 15338 GWh and 2.526 kt CO_2-e (Grid Emissions Factor GEF = 0.165 kt CO_2-e/GWh). Total emissions from the electricity sector is estimated at eight times higher in 2020, having risen from 2523 kt CO_2-e in 2013 to 19600 kt CO_2-e in 2020 to cover increase in demand.

Due to the significant increase in electricity demand in 2030, emissions have been peaked in that year when they are estimated at 29516 kt CO_2-e for 136.60 TWh and the generation mix is hydro 83.44 TWh (67%), gas 16.33 TWh (9 %), coal 30.87 TWh (18%) and renewable 5.96 TWh (7%) as per option 1 in scenario 1.

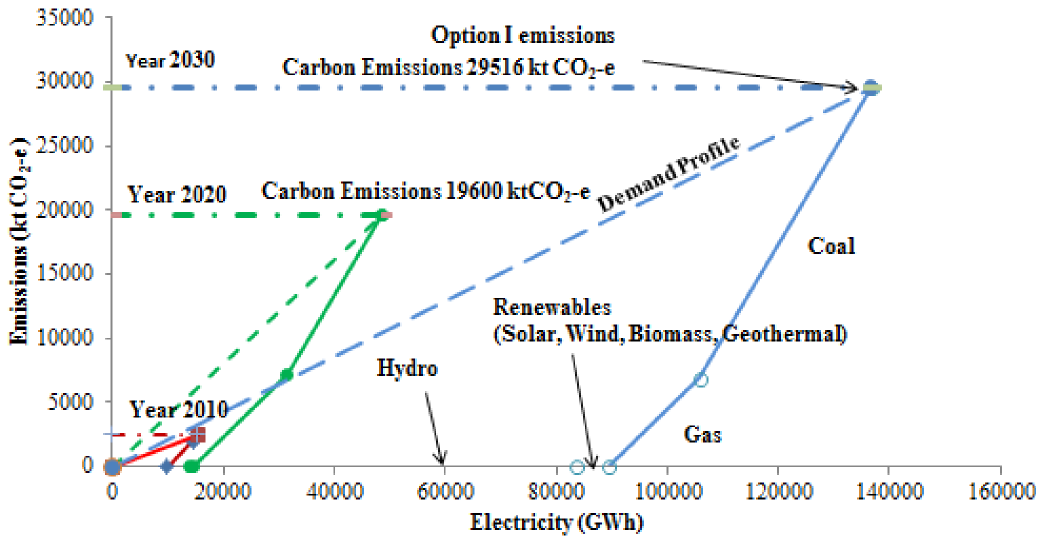


Figure 4.12 Carbon emissions comparison for the year 2010, 2020 and 2030. (Data from Japan International Cooperation Agency et al., 2014, Ministry of Electric Power, 2015 and Walmsley et al., 2014).

Based on CEPA techniques, the best option to reduce emissions in the electricity sector is switching from a resource with a higher emissions factor to one with a lower emissions factor, i.e. coal and gas for renewable resources such as hydro and solar. Thus, changing from coal resources to gas resources as described in option II, the meaningful reductions in emissions from electricity of 5113 kt-CO_2-e (17% reduction) is achieved. Figure 4.13 highlights the 17 % reduction of carbon emissions by using option II in terms of hydro 83.44 TWh, gas 32.78 TWh, and coal 14.42 TWh and renewable 5.96 TWh. In this option, the significant carbon reduction will be by replacing gas 16.45 TWh and by reducing coal 16.45 TWh.

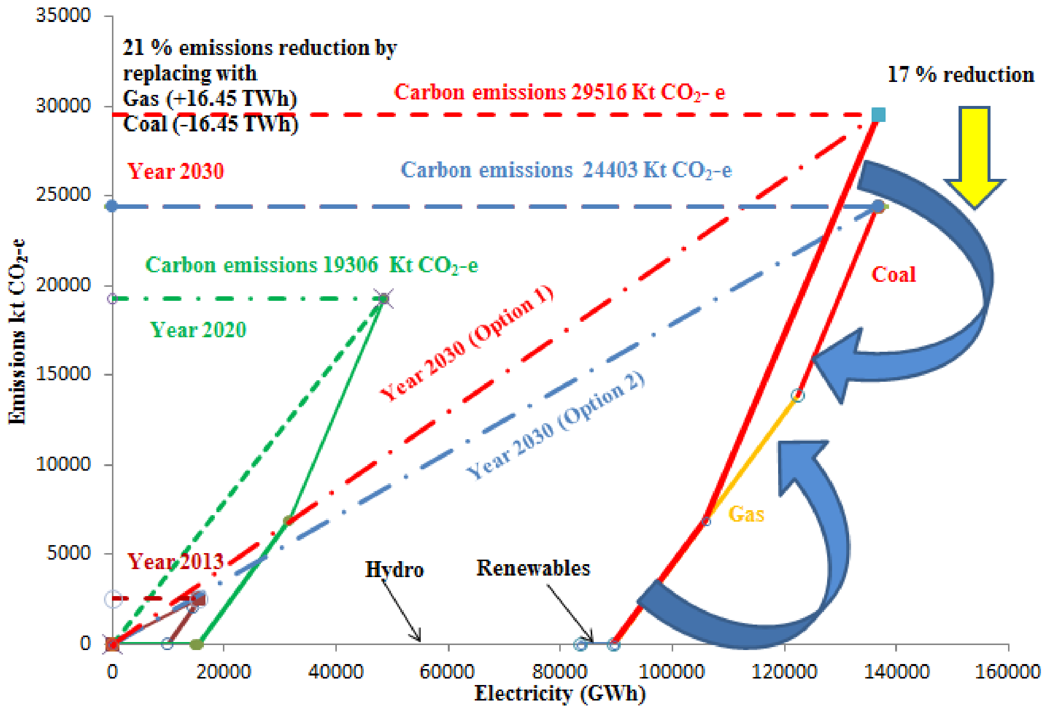


Figure 4.13 Emissions reduction in year 2030 by replacing coal to gas. (Data from Japan International Cooperation Agency et al., 2014, Ministry of Electric Power, 2015 and Walmsley et al., 2014).

4.6.3 Annual Electricity Emissions for Myanmar in 1990, 2000, 2010 and 2011

In this section, the analysis will be focused on the generation mix in Myanmar for the years 1990, 2000, 2010 and 2011 by using the CEPA composite curve method. A comparison of carbon emissions and electricity generation is illustrated in Figure 4.14.The total electricity demand and emissions for Myanmar in 2011 were 9868 GWh and 1228 ktCO_2-e respectively (GEF=0.124 kt CO_2-e/GWh), and the generation mix was 76% hydro, 16% gas, 7% coal and 1 % oil. The total amount generated from renewables was 76%, with the remainder from fossil fuel based thermal generation. Emissions factors were referenced, based on data of New Zealand's Ministry of Economic Development Energy Data Set (Walmsley et al., 2014).

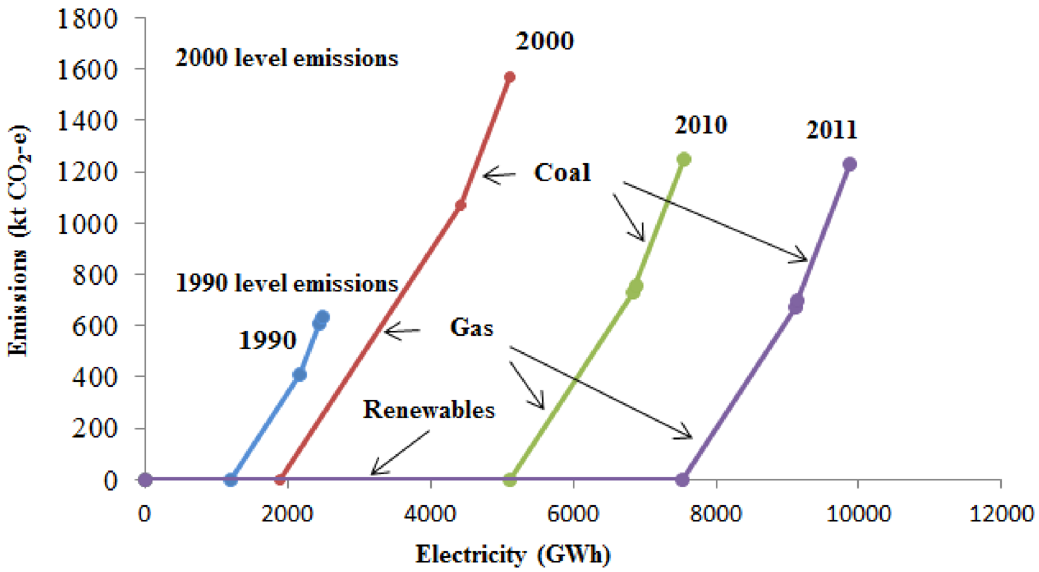


Figure 4.14 A comparison of carbon emissions and electricity generation in Myanmar for the year 1990, 2000, 2010, and 2011. (Data from Ministry of Electric Power, 2015 and Walmsley et al., 2014).

There was no significant shift in the generation mix between 1990 and 2011. While the mix is still dominated by hydropower except in 2000, the amount from natural gas almost trebled between 1990 and 2000 and then roughly doubled between 2010 and 2011. Coal generation was also added to the generation mix starting in 1990 (except 2000), although it is still only a relatively small proportion of the total for each year. Emissions from the electricity sector have almost doubled from 636 kt CO_2-e in 1900 to just less than 1300 kt CO_2-e in 2011. Emissions peaked in 2000 when they were over 1500 kt CO_2-e. There was a 21 % reduction in emissions from 2000 to 2010 due to the significant reduction in the use of gas, although coal was added in the generation mix. Emissions continued to decrease from 2010 to 2011, with a further reduction in coal fired generation and gas generation.

4.6.4 Emissions per Capita Comparison for New Zealand, Australia, the United States and Myanmar

Figure 4.15 illustrates the electricity use per capita and emissions per capita of Myanmar compared with New Zealand, Australia and the United States by the year 2011. The majority of electricity generation in Myanmar come from hydropower, New Zealand come from hydropower and geothermal, while the US and Australia's generation was mainly based on the non-renewables energy resources. Therefore, the emissions per capita of the two former countries were much lower than that of the fossil – fuel based countries. Due to very low electricity generation in Myanmar in 2011 reflects the lowest per capita electricity generation and emissions. New Zealand exploiting the high renewables resources especially hydropower and geothermal for electricity generation, however there would be a shortfall in the renewables resources in the future because of the limited renewable resources. Nonetheless, the emission per capita is controlled by the ratio of renewable and non-renewable generation mix in each country (Walmsley et al., 2014).

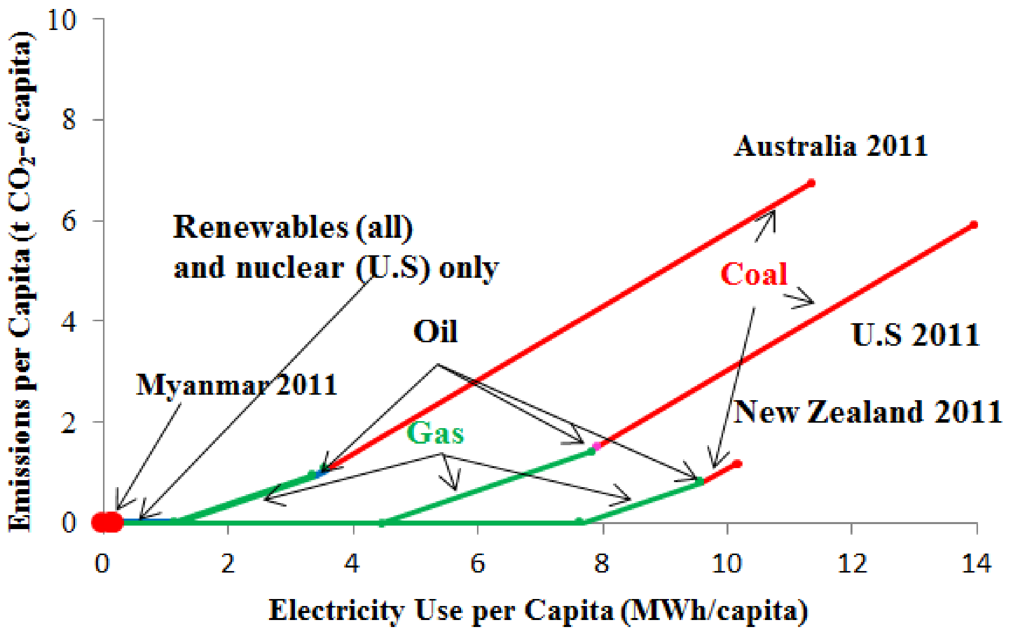


Figure 4.15 Comparisons of generation and emissions profiles among New Zealand, Australia, the United States and Myanmar on a per capita basis by the year 2011. (Data from International Energy Agency, 2016, Ministry of Electric Power, 2015 and The World Bank, 2016).

4.6.5 Emissions Comparison for Electricity Generation

Figure 4.16 illustrates the optimal generation mix for fulfilling future electricity demand of 48.52 TWh in 2020 and 136.66 TWh in 2030 at 1990 and 2011 emissions levels respectively. The optimum values have been determined using a spread sheet optimization tool. As is observed in Figure 4.16, a significant increase in carbon emissions will be reached in 2020 and again in 2030 due to the sharp increase in electricity demand for projected increased population, moderate economic growth and export availability.

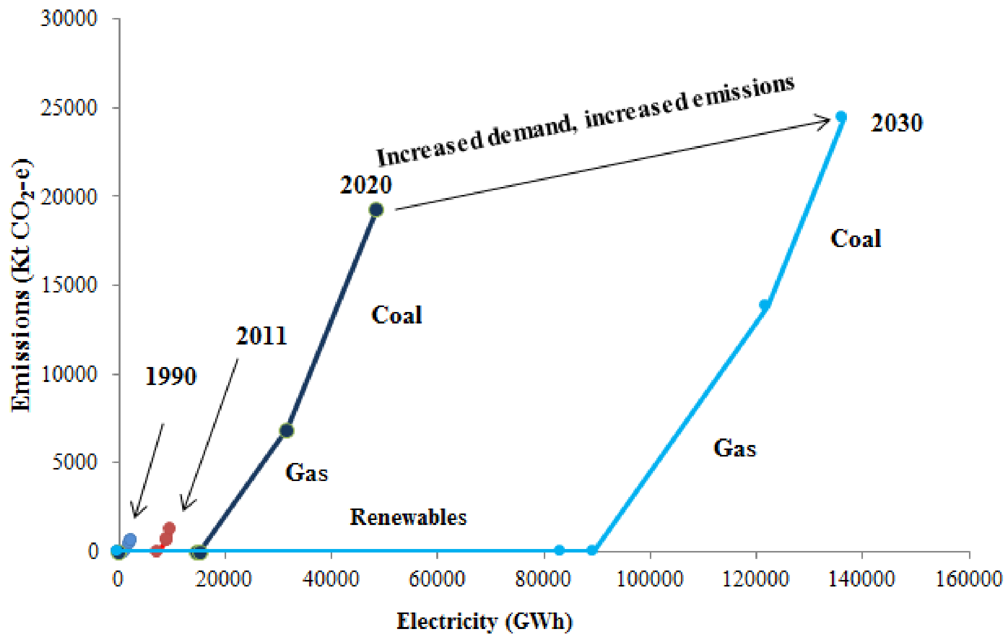


Figure 4.16 Emission comparison of generation mix profiles for the year 1990, 2010, 2020 and 2030. (Data from Japan International Cooperation Agency et al., 2014; Ministry of Electric Power, 2015; Walmsley et al., 2014).

Optimal expansion of generation to meet the future demand 136.66 TWh which would require hydro to increase to 61% of total generation, gas 24%, coal 11% and other renewables such as solar, wind, biomass and geothermal to increase over 4%. For this option, JICA et al., 2014 suggested MOEP to import coal from foreign countries, to adopt Clean Coal Technology (CCT) and to introduce high technology such as Ultra Supercritical Plant (USC plant) (Japan International Cooperation Agency et al., 2014).

4.7 Conclusions

Myanmar can achieve a reasonable goal of carbon emissions reduction by 2030 with the focus clearly on an eight fold expansion of hydro from 2013 levels and an increase in renewables over the same period. With the new technology development of renewable resources such as solar, wind, biomass, and geothermal, and the large hydro power plant extension, the existing capacity will be anticipated to fulfil the requirement of future electricity generation. The formulation of supportive energy policies and implementation of more renewables such as hydro and solar in the energy generation mix to decrease the CO_2 emission to the atmosphere needs to be carried out to accomplish the country's goal.

Chapter 5
Analysis of Energy Return on Investment of Storage Type Hydropower Plants in Myanmar

5.1 Introduction

The installed capacity from the hydropower plants of Myanmar in 2015 is 3151 MW and projected to extend this capacity up to 19000 MW considering carbon emissions constraints in 2030 as discussed in Chapter 4. This achievable goal is significantly supported by the tremendous hydropower potential estimated to be over 40000 MW from the major rivers basins of Myanmar (Khaing, 2015b).

On this account, it has been discussed the possibility of future carbon emissions potentials of the different generation mix target in 2030 based on "The National Electricity Master Plan" (2014-2030) (Japan International Cooperation Agency et al., 2014). As stated in literature review, it is also important to evaluate the projected Energy Return on Investment (EROI) values of the renewable energy sites.

The evaluation of EROI of the hydropower plants is it has a good expression of how much energy returns to society and economy after energy investment in building and running electricity generation infrastructure. The reason is that today's pressure is being put forward by global society that the earth's resources should be utilized as efficiently as possible (Atlason & Unnthorsson, 2014). EROI has been utilized in most of the macro-scale applications as an effective tool to evaluate future energy generation plans for a country (Walmsley et al., 2014). The EROI methodology provides a quantifiable output, which reflects the energy return of each power plant and the feasible energy surplus to the society by analysing energy cost and energy production. The essence of EROI is if a resource provides a high EROI value, the energy production will significantly return to the society, if it provides a low EROI value, the less energy is available to the society (Atlason & Unnthorsson, 2014).

In this chapter, the projected EROI values for the constructed, under-construction and planned hydropower plants in Myanmar, in total 47 power plants are evaluated by using the real data and previously proposed methodology. The analysis of energy production involves the energy used in energy generation, and energy cost involves all the energy used within the energy conversion processes. Hence, as the first section, a brief description of proposed EROI methodology, system boundary and the underlying assumptions are stated (Murphy et al., 2011). Predictive equations derived from Kansai Electric Power Co. Inc. (Mizuta & Takeda, 2015) are applied to estimate the energy costs and energy production of the power plants. The Energy Payback Time (EPT) - the starting time of a specific power plant to deliver the energy surplus to the economy - is also figured out for each power plant. The results and discussion of the projected EROI values for 47 power plants are presented as a final section.

5.2 Methodology and System Boundaries for EROI analysis, Assumptions and Predictive Equations

It has been stated in Chapter 3 that the hydroelectric characteristics and all the elements for the storage type hydropower plants which will be carried out EROI analysis. However, all these parameters are needed to be well fitted into the analysis of EROI. For this purpose, it is needed to state that the relevant methodology, system boundaries, assumptions and predictive equations before EROI projections.

5.2.1 Methodology and System Boundaries for EROI Analysis

The objective of this study is to estimate the $EROI_{stnd}$ values of the storage type hydropower plants, inclusive of the energy costs and energy production for the processed stage of electricity. Hence, the methodology and system boundaries determining EROI have been explained in Section 2.4 of Chapter 2. EROI analysis of this study is based on Equation (2.4) and the generic flow diagram of Figure 2.2 and 2.3. The analyst proposes the system boundary 2 to figure out the $EROI_{stnd}$ analysis (Murphy et al., 2011).

The energy outputs and inputs identified from Figure 2.2 and 2.3 can be briefed as the two dimensional framework in Table 2.2 (Murphy et al., 2011). According to Table, this study will represent "$EROI_{stnd}$" calculation; therefore, different studies of different fuels can also be compared to the results of this study if they use the same boundaries.

As the basic essence of EROI is the ratio of energy output by energy input, the energy output as the numerator of this ratio is need to be expressed first. While this study is based on system boundary 2, direct energy output from the power plants (otherwise annual energy generation) is counted, which coverage of the energy process chain from extraction (mine-mouth) to intermediate processing (refinery gate), but not included the distribution stage (final demand) (Murphy et al., 2011).

In terms of the denominator of $EROI_{stnd}$ ratio, it is also needed to express which are counted as the energy inputs. In that case, based on the level 3 of Figure 2.3 in Chapter 3 (Materials consumption) the embedded energy inputs in the materials for the power plants are counted (Murphy et al., 2011). However the energy chain under the investigation stage is ignored the fact that it is impossible to get the information of the power plants' investigation data because they had been done long time ago. Therefore, as the denominator of $EROI_{stnd}$ ratio, the operational and maintenance energy of the power plants are included, the embodied energy in all the materials used for construction of the plant themselves and appurtenant structures are counted, the embedded energy in the local materials and reinforcement transportation, the imported hydraulic and electro - mechanical equipment transportation to the plant sites are also counted. The energy used at the preparation stage and soil handling state are also included. The hydraulic equipment such as spillway gate, intake gate, intake screen etc., and electro mechanical equipment such as turbines and generators, their embedded energy are also included.

One important thing of $EROI_{stnd}$ calculation is to make the energy quality adjustment between the energy conversion processes which needs to choose a suitable method. Concerning the selection of the energy quality adjustment method, any price information for the storage type hydropower plants is not available, thus it is inconvenient to use "Price-Based Adjustment Method". Therefore, "Exergy-Based Adjustment" is used in this study to make the energy quality correction (Murphy et al., 2011). In this regard, the physical units such as embodied energy data (MJ/kg) are used to adjust for quality differences in all the energy carriers. All these values used in this study are illustrated in Table 5.1.

Table 5.1 Density and embodied energy values for related materials.

Materials	Density (kg/m^3)	Embodied Energy (MJ/kg)	References
Natural soil and rock/ clayey soil	1900	0.45	Al-Jawadi, 2015 Hammond & Jones, 2006
Reinforced Concrete (RC)	2300	1.04	Hammond & Jones, 2006
Concrete (CVC)	2403	0.75	Hammond & Jones, 2006
Aggregate (gravel or crushed rock)	2240	0.083	Hammond & Jones, 2006
Roller Compacted Concrete (RCC)	2420	0.65	Berga et al., 2003 Hammond & Jones, 2006
Asphalt	1700	2.86	Hammond & Jones, 2006
Cement	1860	4.51	Hammond & Jones, 2006
Sand (general)	2240	0.0081	Hammond & Jones, 2006
Steel (bar and rock)	-	21.60	Hammond & Jones, 2006
Steel (structural)	-	31.30	Hammond & Jones, 2006
Steel (stainless)	-	56.70	Hammond & Jones, 2006
Steel (pipe)	-	24.90	Hammond & Jones, 2006
Steel (plate)	-	45.40	Hammond & Jones, 2006
Copper (general)	-	69.02	Hammond & Jones, 2006

The excavation or construction work quantities of the materials such as soil, sand, gravel or crushed rock, Reinforced Concrete (RC), Concrete (CVC) and Roller Compacted Concrete (RCC), etc. are collected as the real data from MOEP or calculated by the predictive equations designed by Kansai Electric Power Co., Inc. Those data are generally accessed in terms of volume (m^3). As they are needed to make the energy quality adjustments, (in terms of the heat equivalent unit - MJ), these values are converted by using the relevant density values (unit mass per volume – kg/m^3) and embedded energy values (embodied energy per unit mass – MJ/kg) as shown in Table 5.1. The reinforcement bars data collected from MOEP or calculated by the predictive equations are generally in terms of mass (ton or kg), then they are also converted to the heat equivalent unit (MJ) by using the embedded energy values (embodied energy per unit mass – MJ/kg) as shown in Table 5.1. Likewise, the energy used in the hydraulic equipment such as intake gate, intake screen, spillway gates and penstocks, and in the electro-mechanical equipment such as turbines and generators are converted to the heat equivalent units (MJ) in the same way.

Besides this, the energy used at the preparation stage, such as the embodied energy usage for the construction of access roads to the project sites and the energy used at the transportation stage, such as trucks or ships used for materials, reinforcement and hydraulic equipment' transportation etc. are converted to the heat equivalent units (MJ) as well. Those estimated embedded energy values are shown in Table 5.2.

Table 5.2 Embodied energy for trucking, roading and shipping.

Components	Embodied Energy	Unit	References
Trucking	2.94	MJ/(t.km)	Walmsley et al., 2015b
Roading	1875000	MJ/km	Ardente et al., 2008
Shipping	0.1129	MJ/(t.km)	Walmsley et al., 2015b

As this study used the Exergy-Based Adjustment method, the readers are informed the following shortcomings. (1) The exergy-based adjustment method is used to make the energy quality adjustment of the data used in this study; the economic data such as prices and inflation are to be avoided (Murphy et al., 2011). (2) This adjustment method cannot capture the properties of fuel or energy carrier contributing to the economic issues, for instance, global warming potential and toxicity etc. (Murphy et al., 2011). (3) This adjustment method also disregards the important inputs such as capital and labour, therefore, any capital and labour issues information are not described (Murphy et al., 2011).

5.2.2 Assumptions

5.2.2.1 Process Electrical Output Data Collection and Assumptions

Real data for all 47 storage type hydropower plants are collected from MOEP with the data included as (1) Power output (Installed capacity, MW) (2) Units of turbines and types (3) Power discharge (volumetric flow rate at each turbine, m^3/s) (4) Effective head (Hydraulic head, m) and (5) Annual energy generation (GWh) (Ministry of Electric Power, 2015). Those data have been described in Table 3.2, 3.3, 3.4 and 3.5 in Chapter 3. As this analysis is process analysis (also known as bottom-up analysis) which is similar to lifecycle analysis, this takes into account energy outputs and inputs by collecting them through the following stages of production in a process (Murphy et al., 2011). Hence, the analysis is based on the life time of the respective power plants. Thus, when calculating $EROI_{stnd}$ values, the numerator of the $EROI_{stnd}$ ratio is defined as Total Process Electrical Output and the denominator of the ratio is defined as Total Process Energy Input. The technical lifetime of all storage type hydropower plants in this study are considered to be 100 years because the previous EROI studies are also used 100-year life time period for hydropower plants (Gagnon, 2002; Atlason & Unnthorsson, 2014).

5.2.2.2 Process Energy Input Data Collection and Assumptions

In this study, the eight parts are included as the Total Process Energy Input of $EROI_{stnd}$ ratio based on 100 - year lifetime. These being (1) Power usage at site (Own usage by the power plant, in other words the operational energy), (2) Maintenance (annual reinvestment), (3) Transportation (4) Groundwork phase (5) Preparation stage (6) Construction stage to the plants site (7) Hydraulic equipment and (8) Electro mechanical equipment. Except the real data gathered from MOEP, the unavailable data are calculated by using the predictive equations designed by Kansai Electric Power Co., Inc. described in the next section. The following assumptions are adopted for the Total Process Energy Input calculation.

1. Operational Energy (Power usage at site)

The own usage of all hydropower plants can be approximated to be 0.5% of their annual energy generation. This value may sometimes vary; however, it is expected to be around this number on average (Atlason & Unnthorsson, 2014).

2. Maintenance (Annual reinvestment)

It is difficult to get the maintenance data the fact that every parts of the hydropower plants need to be maintained throughout their lifetime in terms of daily, weekly, monthly, quarterly, annually, every ten years (for overhauling or capital maintenance) etc. (Operation and Maintenance of Hydropower Stations Planning and Management, n.d). Thus, the energy used in the calculation for the annual reinvestments is only covered under the maintenance topic. According to the life cycle data for hydroelectric generation at Embretsfoss 4 (E4) power station of Norway, the technical lifetime for dams, tunnels and station halls are considered to be 100 years (Arnøy & Modah, 2013, 703). Therefore, the reinvestment energy for these parts is also ignored. For the spillway gate, penstock (conduit), turbines and generators, their technical lifetime is considered to be 60 years (Arnøy & Modah, 2013). Therefore, the annual reinvestment energy is accounted for 1.6% of the original appliances' embodied energy. For the lifetime of intake gate and intake screen, they are estimated to be 50 years and 35 years (MESA Associates, 2012). Therefore, the annual reinvestment energy is accounted for 2 % and 2.8 % of their embodied energy respectively.

3. Transportation

All the construction materials such as soil, sand, aggregate (gravel or crushed rock); Conventional Vibrated Concrete (CVC) and Reinforced Concrete (RC) are assumed to be transported within 10 km distance from the plant sites. The reason is all the construction materials are needed to be available within the economical distance (US Army Corps, 2004). The 10 km distance is referred from the project report of Shwegyin (Ministry of Electric Power, 2015). For RCC dam types, Roller Compacted Concretes (RCC) are considered to be transported from Pozzolan factory at Popa, Mandalay Region, the central part of Myanmar. For the reinforcement bars, if the operators or Joint Venture Companies are known, they are assumed to be transported from the specific location of those companies whether those companies are located in Myanmar or other countries. If the power plants are located at the lower part of the country, the reinforcement bars are assumed to be transported from Myaung Tagar Factory, Myanmar Economic Corporation (Ministry of Electric Power, 2015). Otherwise, if the plants are located the upper parts of the country; they are assumed to be transported from the factories in Harbin, The People Republic of China. In the case of hydraulic equipment and electro-mechanical equipment, the transportation distances for all power plants are considered according to the joint venture partner company's name and location of those companies. If the company names are unknown, they are assumed to be transported from Harbin, The People Republic of China (Ministry of Electric Power, 2015).

4. Ground work phase

The groundwork phase is described under the Section 5.2.3.

5. Preparation stage

As the preparation stage of the power plant, access roads, camp and facilities for all hydropower plants are needed to be considered (Mizuta & Takeda, 2015). However, due to the data unavailability, only the energy embedded in the access roads is calculated in this study. The access roads distances are provided by the project proposals (Ministry of Electric Power, 2015). In case they are unknown, the distances can be estimated on Google map by using the sites' specific location, meaning the distance between the specific dams' location and the closest main roads next to the dams.

6. Construction stage

At the construction stage, the temporary civil work quantities such as grouting, coffering and saddle dams are ignored. The civil engineering work quantities such as the excavation volumes, the construction volumes and the reinforcement bars for dams, spillways, intake, headrace, surge tank, penstock, powerhouse, tailrace channel and tailrace outlet are considered (Mizuta & Takeda, 2015) The fundamental data for all power plants are described in Tables 3.6, 3.7, 3.8, 3.9, 3.10 and 3.11 and some work quantities for under-construction power plants are described in Table 3.12 in Chapter 3. For the power plants those work quantities are not available, they are needed to guestimate by using the predictive equations, and the relevant assumptions are also described. Thus, it would bring the easy access for the $EROI_{stnd}$ analysis for all hydropower plants. The predictive equations and relevant assumptions for all those parts are described under the Section 5.2.3.

7. Hydraulic equipment

The predictive equations and assumptions for the hydraulic equipment, such as the weight of intake gates, intake screens, spillway gates, penstock (conduits) are also discussed under the Section 5.2.3.

8. Electro-mechanical equipment

The predictive equations and assumptions for the electro-mechanical equipment, such as turbines and generators are also discussed under the Section 5.2.3.

5.2.3 Predictive Equations

All the predictive equations described in this section are provided by Kansai Electric Power Co., Inc. (Mizuta & Takeda, 2015).

(1). Dam Volume (Excavation)

For both gravity and fill dam types, the work quantity for excavation volume is calculated by using Equation (5.1) if it is unknown.

$$V_e = 10 \times H_d \times L \tag{5-1}$$

Where V_e is the dam excavation volume (m^3), H_d is dam height (m) and L is dam crest length (m). The dam height (H_d) and Dam crest length (L) are exemplified as shown in Figure 5.1.

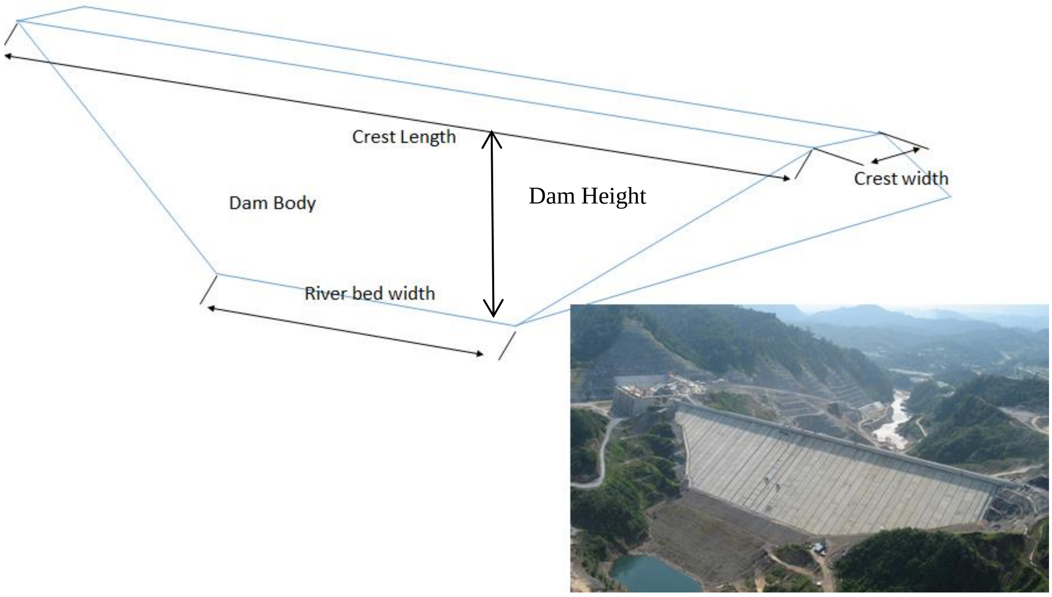


Figure 5.1 Example of dam height and dam crest length (Mizuta & Takeda, 2015).

Assumptions

For constructed and planned power plants, dam excavation volume (V_e) is determined by Equation (5.1), in which the dam height (H_d) and dam crest length (L) for all the power plants have been provided in Tables 3.8 and 3.9 in Chapter 3. For the under-construction power plants, the real data for the dam excavation volume are provided by MOEP and described in Table 3.12 in Chapter 3 (Ministry of Electric Power, 2015).

(2) Dam Volume (Embankment – Fill Dam)

In the case of fill dam, both earth-fill and rock-fill dam: Homogeneous Earth-Fill Dam (HEFD), Zone Type Earth-Fill Dam (ZTEFD), Zone Type Rock-Fill Dam (ZTRFD) and Concrete Faced Rock-Fill Dam (CFRFD), the embankment volume is calculated by using Equation (5.2) if it is unknown.

$$V_f = \frac{1}{6} \times (m + n) \times H_d^2 \times (L + 2B) + \frac{W}{2} \times H_d \times (L + B) \quad (5\text{-}2)$$

V_f is dam embankment volume (m^3), H_d is dam height (m), L is dam crest length (m), B is river bed width (m), W is dam crest width (m), m is upstream slope of dam, n is downstream slope of dam.

Assumptions

For both constructed and under-construction power plants, the real data for dam embankment volumes are provided by MOEP and have been described in Table 3.8 in Chapter 3 (Ministry of Electric Power, 2015). For planned projects, dam embankment volumes are estimated by using Equation (5.2). In this regard, the dam height, dam crest length and river surface width are described in Table 3.9 in Chapter 3. Dam crest width (W) is assumed as 10 m which is referenced from Ann hydropower plant (Mizuta & Takeda, 2015). The values of the upstream slope of dam (m) and downstream slope of dam (n) are considered as 2.0 and 1.8 as per manual of Kansai Electric Co.Ltd.

(3) Dam Volume (Construction – Gravity Dam)

Gravity dam type consists of Conventional Vibrated Concrete (CVC) and Roller Compacted Concrete (RCC). In the case of gravity dam's construction volume calculation, the equations for both CVC and RCC dams are the same. Hence, it is firstly needed to consider the value of $Hd^2 \times L$, whether which is less than or equal to 100×10^3 or greater than that value. After deciding the value of $Hd^2 \times L$, the dam construction volume is calculated by using the relevant equations.

In the case of $Hd^2 \times L \leqq 100 \times 10^3$, river bed width (B) and dam crest length (L) is needed to be decided first. If the ratio of B/L is equal to 0.5, dam construction volume is calculated by using Equation (5.3).

$$V_c = 38 \times (H_d^2 \times L)^{0.59} \quad (5\text{-}3)$$

Where, V_c is concrete volume (m^3), H_d is dam height and L is dam crest length (m). If B/L is 0.4, dam construction volume is calculated by using Equation (5.4).

$$V_c = 35.5 \times (H_d^2 \times L)^{0.59} \quad (5\text{-}4)$$

If B/L is 0.3, dam construction volume is calculated by using Equation (5.5).

$$V_c = 32.4 \times (H_d^2 \times L)^{0.59} \quad (5\text{-}5)$$

If B/L is 0.2, dam construction volume is calculated by using Equation (5.6).

$$V_c = 27.5 \times (H_d^2 \times L)^{0.59} \quad (5\text{-}6)$$

If B/L is 0.1, dam construction volume is calculated by using Equation (5.7).

$$V_c = 22.4 \times (H_d^2 \times L)^{0.59} \quad (5\text{-}7)$$

Likewise, in the case of $H_d^2 \times L > 100 \times 10^3$, the ratio of river bed width (B) and dam crest length (L) is needed to be decided first. Then, dam construction volume is calculated by using corresponding to B/L ratio. If the ratio of B/L is equal to 0.5, dam construction volume is calculated by using Equation (5.8).

$$V_c = 0.34 \times (H_d^2 \times L) \quad (5\text{-}8)$$

If B/L is 0.4, dam construction volume is calculated by using Equation (5.9).

$$V_c = 0.30 \times (H_d^2 \times L) \quad (5\text{-}9)$$

If B/L is 0.3, dam construction volume is calculated by using Equation (5.10).

$$V_c = 0.27 \times (H_d^2 \times L) \quad (5\text{-}10)$$

If B/L is 0.2, dam construction volume is calculated by using Equation (5.11).

$$V_c = 0.21 \times (H_d^2 \times L) \quad (5\text{-}11)$$

If B/L is 0.1, dam construction volume is calculated by using Equation (5.12).

$$V_c = 0.16 \times (H_d^2 \times L) \quad (5\text{-}12)$$

Assumptions

For all the constructed and under-construction power plants, dam construction volume, V_c, are provided by MOEP except Chi Phwae Nge (99 MW) power plant. Therefore, the dam construction volume for Chi Phwae Nge power plant and all the planned power plants are estimated by the above-mentioned ways. The river surface widths, B for those power plants have been described in Table 3.9 in Chapter 3.

(4) Spillway Calculation (Gravity dam)

In the case of gravity dam, the work quantity of spillway does not need to calculate due to the fact that spillway are generally embedded in dam body. But, if the spillway is gated type, it is needed to calculate the weight of spillway gates by using Equation (5.13). However, if the spillway is un-gated type, it is not needed to calculate the weight of gates.

$$W_g = 0.13 \times Q_f \tag{5-13}$$

W_g is weight of gate (ton), Q_f is design flood discharge (m^3/s). Design flood discharge, Q_f is defined as the maximum peak flow of water (m^3/s) into the reservoir.

Design flood discharge, Q_f, is calculated by Equation (5.14).

$$Q_f = q \times A \tag{5-14}$$

In which q is specific discharge ($m^3/s/km^2$), A is Catchment Area, (km^2).

The unit of specific discharge, q is $m^3/s/km^2$, and that of design flood discharge is m^3/s. Design flood discharge is determined with the whole catchment area at a plant site, which is calculated by multiplying the specific discharge and the whole catchment area by Equation (5.14). The larger catchment area shows low specific discharge, the smaller catchment area shows high specific discharge because it does not rain equally on all the catchment area. It may rain equally in case of huge wide area whereas it does not rain equally in case of small catchment area (Mizuta & Takeda, 2015).

Specific discharge, q is calculated by Equation (5.15), in which "a" is Region Coefficient (unit-less) and A is catchment Area (km^2). The catchment areas of all power plants have been described in Table 3.6 and 3.7 in Chapter 3. Although Region Coefficient, "a" is estimated by using annual rainfall, in which it can be used as 44, this value is designed for Japan and Myanmar' hydropower plants (Mizuta & Takeda, 2015).

$$q = a \times A^{(A^{-0.05}-1)} \tag{5-15}$$

(3) Spillway Calculation (Fill Dam)

In the case of fill dam, the excavation volume (V_e), concrete volume (V_c), weight of reinforcement bars (W_r), and weight of gates (W_g) for spillways are calculated by Equations (5.16), (5.17), (5.18) and (5.19) if they are unknown.

$$V_e = 84 \times Q_f^{1/2} \times H_d \quad (5\text{-}16)$$

$$V_c = 13 \times Q_f^{1/2} \times H_d \quad (5\text{-}17)$$

$$W_r = 0.020 \times V_c \quad (5\text{-}18)$$

$$W_g = 0.22 \times Q_f \quad (5\text{-}19)$$

Where, V_e is excavation volume (m^3), V_c is concrete volume (m^3), W_r is weight of reinforcement bars (ton), W_g is weight of gates (ton), Q_f is design flood discharge (m^3/s), H_d is dam height (m). Design flood discharge, Q_f is calculated by the above-mentioned ways by Equation (5.14).

Assumptions:

A few work quantities for spillways for the under-construction power plants are described in Table 3.12 in Chapter 3. It is needed to calculate the spillways work quantities for the constructed, some under-construction and planned power plants. To calculate the work quantities of spillway, the catchment areas of all power plants have been described in Table 3.6 and 3.7 in Chapter 3. The dam heights for all power plants are described in Table 3.8 and 3.9 in Chapter 3.

(5) Intake

Civil work quantities for intake, excavation volume (V_e), construction volume (V_c), weight of reinforcement bars (W_r), weight of gate (intake gate) (W_g) and weight of Screen (intake screen) (W_s) are calculated by using Equations (5.20), (5.21), (5.22), (5.23) and (5.24) if they are unknown.

$$V_e = 130 \times \left[\{(h_a + D) \times Q\}^{1/2} \times n^{1/3}\right]^{1.27} \quad (5\text{-}20)$$

$$V_c = 56.5 \times \left[\{(h_a + D) \times Q\}^{1/2} n^{1/3}\right]^{1.27} \quad (5\text{-}21)$$

$$W_r = 0.04 \times V_c \quad (5\text{-}22)$$

$$W_g = 0.9 \times (h_a + D)^{1/9} \times Q \quad (5\text{-}23)$$

$$W_s = 0.5 \times (h_a + D)^{1/9} \times Q \quad (5\text{-}24)$$

In which, V_e is excavation volume (m^3), V_c is concrete volume (m^3), W_r is weight of reinforcement bars (ton), W_g is weight of intake gate (ton) and W_s is weight of intake screen (ton), h_a is the available drawdown (m), D is inner diameter of waterway (intake) (m), Q is maximum unit discharge (m^3/s), meaning that it is equal to the maximum plant discharge (or total flow or Power discharge at the turbines - m^3/s) divided by the number of waterway, whereas n is the number of waterway. The volumetric flow rates at each turbine for all power plants are described in Table 3.2 and 3.3 in Chapter 3. It is noted that the maximum unit discharge and volumetric flow rate at each turbine are the same; the maximum plant discharge can be calculated by multiplying the number of turbines and the maximum unit discharge or volumetric flow rate at each turbine described in Table 3.2.

Assumptions:

Some work quantities for intakes for under-construction power plants are described in Table 3.12 in Chapter 3. It is needed to calculate the intake work quantities for the constructed, some under-construction and planned power plants. Hence, the available drawdown h_a is calculated by subtracting minimum drawdown level from full reservoir level of each power plant; those level values have been described in Table 3.6 and Table 3.7 in Chapter 3. For those unknown power plants, the value is assumed as 10 m. Q is maximum unit discharge (m^3/s), meaning that it is equal to the maximum plant discharge (or total flow or Power discharge at the turbines - m^3/s) divided by the number of waterway, whereas n is the number of waterway. The volumetric flow rates at each turbine for all power plants are described in Table 3.2 and 3.3 in Chapter 3. Hence, the data for inner diameter of intake (D) and the number of waterway (n) are described in Table 3.10 and 3.11in Chapter 3 for a few power plants. However, the inner diameter of intake and the number of waterways for most of the power plants are unknown. If the number of waterway (intake) is unknown, it can be estimated corresponding to the number of headrace tunnel (if they are included in the waterway system). If the headrace tunnel is not included in the waterway system, the numbers of waterway (intake) is estimated corresponding to the number of penstock. If the inner diameter of waterway (intake), D (m) is unknown, it can be figured out from Figure 5.2and Equations (5.25) (5.26) and (5.27).

It is already explained that the waterway or the water conveying system of the hydropower plant are defined as headrace tunnel, surge tank, penstock and tailrace, if the inner diameters of those are unknown (except penstock), they can be calculated the same way as the inner diameter of intake finding ways. The inner diameters of penstocks are known in most cases. However, if they are unknown, they can also be figured out. The explanation is described under the topic of penstock.

For intake, a pressure type intake is adopted, and the inner diameter of waterway (D) is calculated from the Figure 5.2 if it is unknown. In Figure 5.2, the maximum plant discharge or design discharge of waterway, Qmax is designed up to 150 m^3/s. Hence, the inner diameter of waterway (D) can be calculated from Equation (5.25) if Q (the real data of power plant) is less than or equal to the designed Qmax, 150 m^3/s,

$$D = 1.0602413 \times Q^{0.3688377} \tag{5-25}$$

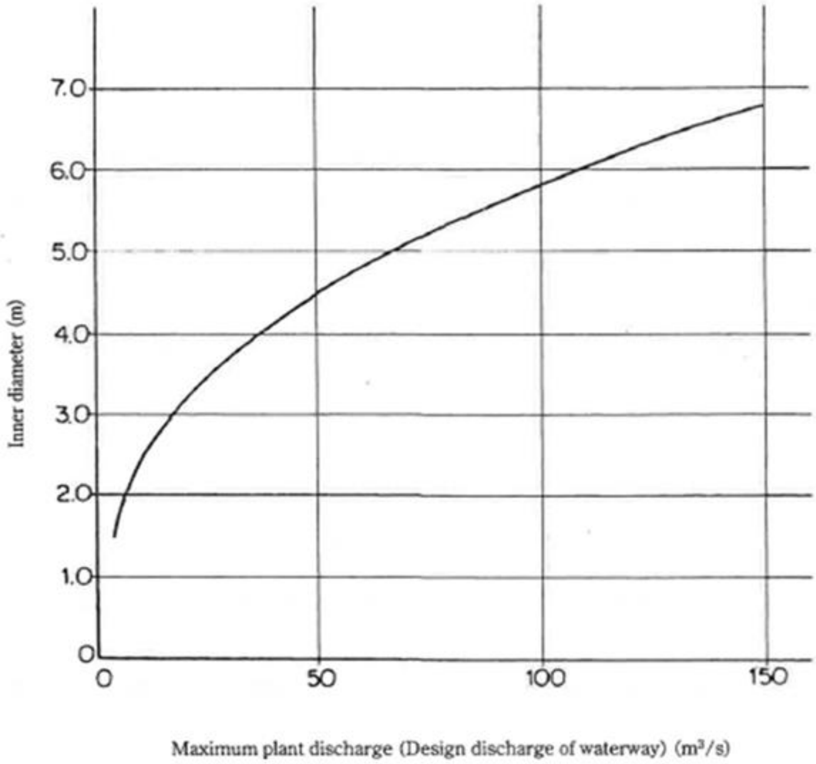


Figure 5.2 Inner diameter of waterway (Mizuta & Takeda, 2015).

In some cases, the maximum unit discharge, Q of waterway (the real data of the plant) can be greater than Q_{max}, 150 m^3/s. In this regard, the inner diameter of waterway, D cannot be directly calculated from the Equation (5.25). Hence, the calculation steps are follows:

By using the designed discharge, Q_{max} value of 150 m^3/s in Equation (5.25) resulted in designed D_{max} value of 6.44 m. After that, the coefficient, r is calculated from Equation (5.26) by using Q_{max} and D_{max} values, resulted in r value of 3.62.

$$Q = r \times D^2 \tag{5-26}$$

After calculating the coefficient r, inner diameter of waterway, D can be calculated again by using Equation (5.26) with the maximum unit discharge of Q (the real data of the plant).

(4) Headrace

A circular fully lined pressure tunnel is adopted. The excavation volume of the pressure tunnel, concrete volume, and weight of reinforcement bars are calculated by the following Equations (5.27), (5.28) and (5.29).

$$V_e = 3.2 \times (R + t_o)^2 \times L \times n \tag{5-27}$$

$$V_c = \{3.2 \times (R + t_o)^2 - \pi R^2\} \times L \times n \tag{5-28}$$

$$W_r = 0.04 \times V_c \tag{5-29}$$

Where, V_e is excavation volume (m^3), V_c is concrete volume (m^3), W_r is weight of reinforcement bars (ton), R is the tunnel radius (m), to is the lining concrete thickness (m), L is the length of the headrace tunnel and n is the number of headrace tunnel.

The tunnel radius, R can be calculated by dividing the inner diameter of waterway with 2. However, if it is unknown case, the value can be calculated from Figure 5.2 by using the above-mentioned way as intake by using Equations (5.25) and (5.26). The lining concrete thickness, to is calculated from Figure 5.3 (Upper line will be used because of the geology is unknown).

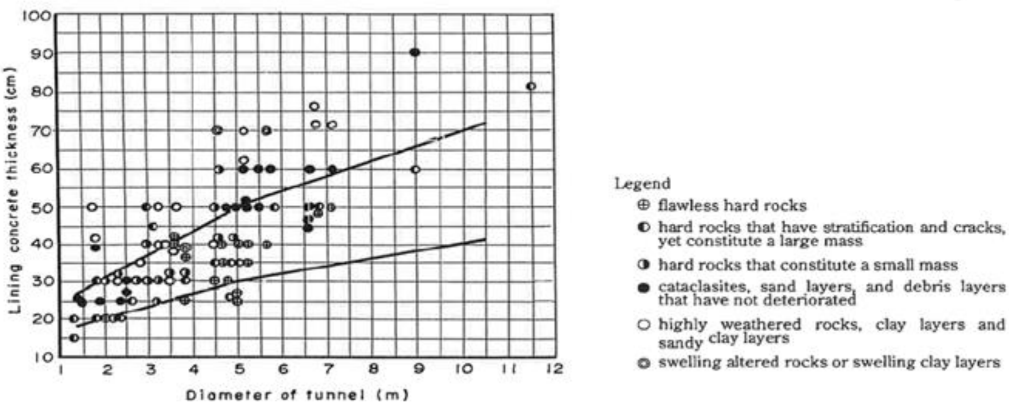


Figure 5.3 Relationships between inner diameter of tunnel and lining concrete thickness (Mizuta & Takeda, 2015).

If the tunnel diameter, D is less than or equal to 5 m, "t_o" is calculated from Equation (5.30),

$$t_o = 0.0643 \times D + 0.1786 \tag{5-30}$$

If the tunnel diameter D is greater than 5 m, "t_o" is calculated by using Equation (5.31).

$$t_o = 0.04 \times D + 0.3 \tag{5-31}$$

Assumptions

A few work quantities of headrace tunnels for under construction power plants are described in Table 3.12 in Chapter 3. The inner diameter, length and the number of headrace tunnel are provided for all hydropower plants (except the diameter of headrace tunnel in Middle Paunglaung) in Table 3.10 and Table 3.11 in Chapter 3. For unknown diameter case, the value can be calculated from Figure 5.2 by using the above-mentioned way as intake by Equations (5.25) and (5.26). The lining concrete thickness, to can be calculated from Figure 5.3 and either Equation (5.30) or (5.31).

(5) Surge tank

The excavation volume, concrete volume, and weight of reinforcement bars are calculated from the Equations (5.32), (5.33) and (5.34).

$$V_e = 38 \times q \times (h_a + L)^{1/4} \times n \tag{5-32}$$

$$V_c = 11 \times q \times (h_a + L)^{1/4} \times n \tag{5-33}$$

$$W_r = 0.05 \times V_c \tag{5-34}$$

Where, V_e is excavation volume (m^3), V_c is concrete volume (m^3), W_r is weight of reinforcement bars, q is Design discharge (m^3/s) equivalent to the maximum plant discharge when the waterway has only one channel, h_a is available drawdown (m), L is the total length of waterway (headrace) (m), n is the number of waterway. It is noted that a surge tank is not provided when the length of waterway is less than 500 m, meaning the work quantities for surge tank are is not needed to calculate if the headrace tunnel length is less than 500 m.

Assumptions

There is no assumption on surge tank as long as the data available for headrace tunnel as the data required for calculating the work quantities of surge tank are the same as headrace tunnel.

(6) Penstock

For exposed type of penstock, the excavation volume, V_e is calculated by using either Equation (5.35) or (5.36) or (5.37) depending on the inner diameter of penstock, Dm. The concrete volume, V_c is calculated by using either Equation (5.38) or (5.39) or (5.40) depending on the inner diameter of penstock, D_m. The weight of reinforcement bars, W_r, is calculated by the Equation (5.41) after calculating V_c.

If inner diameter of penstock D_m is less than or equal to 2 m ($D_m \leqq 2$), the excavation volume V_e is calculated by Equation (5.35).

$$V_e = 10.9 \times D_m^{1.33} \times L \tag{5-35}$$

Where D_m is the inner diameter of penstock (m) and L is the total length of penstock (m). If inner diameter of penstock D_m is greater than 2 m and less than or equal to 3 m ($2.0 < D_m \leqq 3.0$), the excavation volume V_e is calculated by Equation (5.36).

$$V_e = (10.5 \times D_m^2 - 10.5 \times D_m + 12) \times n^{1/3} \times L \tag{5-36}$$

Where n is the number of penstock. If inner diameter of penstock D_m is greater than 3 m ($D_m>3.0$), the excavation volume V_e is calculated by Equation (5.37).

$$V_e = (20.3 \times D_m^2 - 49.5 \times D_m + 41.3) \times n^{1/3} \times L \tag{5-37}$$

If inner diameter of penstock D_m is less than or equal to 2 m ($D_m \leqq 2.0$), the concrete volume V_c is calculated by Equation (5.38).

$$V_c = 2.14 \times D_m^{1.68} \times L \tag{5-38}$$

If inner diameter of penstock D_m is greater than 2 m and less than or equal to 3 m ($2.0 < D_m \leqq 3.0$), the concrete volume V_c is calculated by Equation (5.39).

$$V_c = (0.25 \times D_m^2 + 3.25 \times D_m) \times n^{1/3} \times L \tag{5-39}$$

If inner diameter of penstock D_m is greater than 3 m ($D_m>3.0$), the concrete volume V_c is calculated by Equation (5.40).

$$V_c = (0.5 \times D_m^2 + 2.5 \times D_m) \times n^{1/3} \times L \tag{5-40}$$

$$W_r = 0.018 \times V_c \tag{5-41}$$

Where, W_r is weight of reinforcement bar (ton).

For embedded type of penstock, the excavation volume, V_e, the concrete volume, V_c and the reinforcement weight, W_r are obtained by the following Equations (5.42), (5.43) and (5.44) by assuming thickness of backfill concrete, t is 60 cm.

$$V_e = \frac{\pi}{4} \times (D_m + 2t)^2 \times L \times n \qquad (5\text{-}42)$$

$$V_c = \frac{\pi}{4} \times \{D_m + 2t^2 - {D_m}^2\} \times L \times n \qquad (5\text{-}43)$$

$$W_r = 0.012 \times V_c \qquad (5\text{-}44)$$

Where, D_m is the average inner diameter of steel pipe (m), t is the thickness of backfill concrete (60 cm), L is the total length of penstock (m) and n is the number of penstock.

The weight of steel conduit, W_p for exposed type is calculated by the following Equation (5.45) after calculating t_m from Equation (5.46).

$$W_p = 7.85 \times \pi \times D_m \times t_m \times 1.15 \times L \times n \qquad (5\text{-}45)$$

$$t_m = 0.0313 \times H \times D_m + 2 \qquad (5\text{-}46)$$

Where, t_m is thickness of steel conduit (mm) and H is Design head (m). Design head is calculated by subtracting tail water level (which is the water level at the turbine) from Full Reservoir Level. If the tail water level unknown, the design head is assumed to the same as the effective head (H_e).

For embedded type of penstock, the excavation volume, V_e, the concrete volume, V_c and the weight of reinforcement bars, W_r are calculated by the Equations (5.48), (5.49) and (5.50).

$$V_e = \frac{\pi}{4} \times (D_m + 2t)^2 \times L \times n \qquad (5\text{-}47)$$

$$V_c = \frac{\pi}{4} \times \{\left((D_m + 2t)^2 - {D_m}^2\right)\} \times L \times n \qquad (5\text{-}48)$$

$$W_r = 0.012 \times V_c \qquad (5\text{-}49)$$

The weight of steel conduit, W_p for embedded type is calculated by the following Equation (5.51) after calculating tm from Equation (5.52).

$$W_p = 7.85 \times \pi \times D_m \times t_m \times 1.10 \times L \times n \qquad (5\text{-}50)$$

$$t_m = 0.0313 \times H \times D_m + 2 \qquad (5\text{-}51)$$

Where, W_p is the weight of steel conduit (ton), D_m is the inner diameter of penstock (m), L is the length of penstock (m), n is the number of penstock, tm is thickness of steel conduit (mm) and H is Design head (m). Design head is calculated by subtracting tail water level (which is the water level at the turbine) from Full Reservoir Level. If the tail water level unknown, the design head is assumed to the same as the effective head (H_e).

The above stated equations from Equations (5.35) to (5.51), can be used if the average inner diameter of penstock, D_m is known. Most of the penstock specifications of hydropower plants in Myanmar have been stated in the Table 3.10 and 3.11 in Chapter 3. If the average inner diameter of penstock, D_m is unknown, it can be calculated from Equation (5.25) (under the section of intake) by using the power plant unit discharge Q, if it is less than or equal to the design discharge Q_{max}, 100 m^3/s as shown in Figure 5.4.

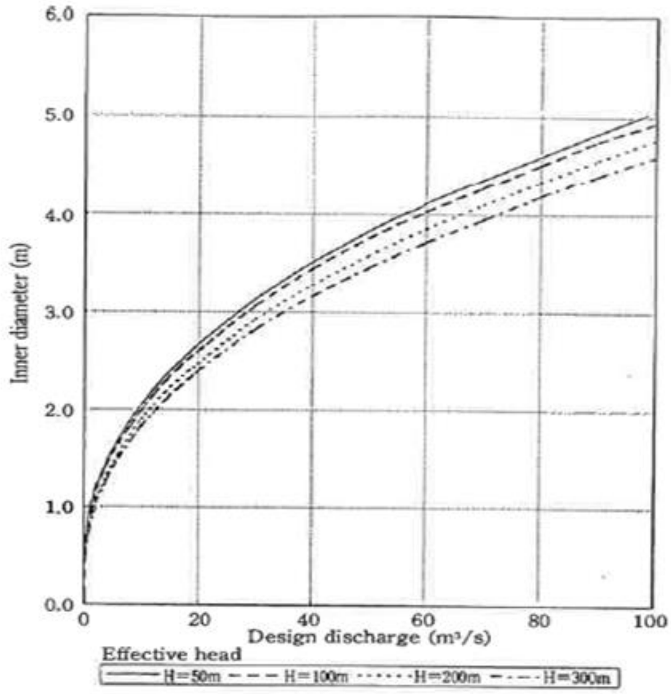


Figure 5.4 Inner diameter of penstock (Mizuta & Takeda, 2015).

If the plant unit discharge, Q is greater than the design discharge Q_{max}, 100 m^3/s, the inner diameter of penstock, D can be calculated by following steps:

Calculate the inner diameter of designed penstock, D_{max} by using either Equation (5.52) or (5.53) or (5.54) or (5.55) depending on the effective head (H_e) (m) and maximum design discharge, Q_{max} = 100 m^3/s.

If effective head H_e is greater than 250 m,

$$D = 0.0841 \times Q^{0.355} \quad (5\text{-}52)$$

If effective head H_e is greater than 150 m,

$$D = 0.0853 \times Q^{0.361} \quad (5\text{-}53)$$

If effective head H_e is greater than 75 m,

$$D = 0.0876 \times Q^{0.367} \quad (5\text{-}54)$$

If effective head H_e is less than 75 m,

$$D = 0.888 \times Q^{0.370} \quad (5\text{-}55)$$

After calculating the value of D_{max} by using Q_{max} = 100 m^3/s, the coefficient, r is calculated by using Equation (5.26). Then, substitute the value of coefficient, r and the discharge Q of the plant in Equation (5.26) and calculate the diameter of the penstock, D again.

Assumptions

For most of the hydropower plants, the penstock diameter, length, number of penstock and type of penstock are described in Table 3.10 and 3.11 in Chapter 3 (Ministry of Electric Power, 2015). However, for some power plants, the penstock diameters are unknown, in which those values can be calculated by the stated above ways. In addition, there are some cases that do not mention the penstock type for some power plants. In this regard, it is suggested to use the embedded type of penstock (Mizuta & Takeda, 2015).

(7) Powerhouse

If the power house is the above-ground type, Equations (5.56), (5.57) and (5.58) are used to calculate the excavation volume V_e (m^3), the concrete volume V_c (m^3) and the weight of reinforcement bars W_r (ton).

$$V_e = 97.8 \times \left(Q \times H_e^{2/3} \times n^{1/2}\right)^{0.727} \quad (5\text{-}56)$$

$$V_c = 28.1 \times \left(Q \times H_e^{2/3} \times n^{1/2}\right)^{0.795} \quad (5\text{-}57)$$

$$W_r = 0.05 \times V_c \quad (5\text{-}58)$$

Where V_e is excavation volume (m^3), V_c is the concrete volume (m^3) and W_r is the weight of reinforcement bars (ton), Q is the maximum plant discharge (m^3/s) (other words, total volumetric flow rate at the turbines), H_e is effective head (m), n is the number of power house.

If power house is the under-ground type, the Equations (5.59), (5.60), (5.61) and (5.62) are used to calculate the excavation volume V_e (m^3), the concrete volume V_c (m^3), and weight of reinforcement bars W_r (ton).

$$V_e = 27 \times A + 1.3 \times A \times d \tag{5-59}$$

$$V_c = 15 \times A \tag{5-60}$$

$$W_r = 0.6 \times A \tag{5-61}$$

$$A = 20 \times Q^{\frac{1}{2}} \times H_e^{\frac{1}{3}} \tag{5-62}$$

Where V_e is excavation volume (m^3), V_c is the concrete volume, (m^3) and Wr is the weight of reinforcement bars (ton), A is area of powerhouse (m^2), d is height of powerhouse, (m), Q is the maximum plant discharge (m^3/s) (other words, total volumetric flow rate at the turbines), H_e is effective head (m), n is the number of power house.

Assumptions

For all hydropower plants, the volumetric flow rate at each turbine (to calculate the maximum plant discharge, Q) and effective head, H_e are described in Table 3.2 and Table 3.3 in Chapter 3.The powerhouse type, powerhouse specification (length × width × height) for most of the power plants are described in Table 3.10 and 3.11 in Chapter 3 (Ministry of Electric Power, 2015). In this regard, the power house specification are not available for some power plants, however, for the above ground type power house, the work quantities can be calculated without knowing the specification the fact that Equations (5.56), (5.57) and (5.58) depend on the data of maximum plant discharge, Q and effective head, H_e which are known data.

(8) Tailrace Tunnel/Channel

For the tailrace tunnel type, the work quantities for tailrace tunnel are applied the same as Headrace Equations, from Equation (5.27) to (5.31) are used to calculate the excavation volume, V_e, the concrete volume, V_c, the weight of reinforcement bars, W_r, tunnel diameter D and lining concrete thickness t_o.

For the tailrace channel type, from Equations (5.63) to (5.67) are applied.

$$B = (Q)^{\frac{1}{2}} \tag{5-63}$$

$$H = 1.09 \times (Q^{0.379})^2 / B \tag{5-64}$$

$$V_e = 6.22 \times [(B \times H)^{\frac{1}{2}}]^{1.04} \times L \tag{5-65}$$

$$V_c = [H \times t \times 2 + (B + 2 \times t)t] \times L \tag{5-66}$$

$$Wr = 0.0577 \times (\frac{V_c}{L})^{0.888} \times L \tag{5-67}$$

Where excavation volume, V_e (m^3), the concrete volume, V_c (m^3), the weight of reinforcement bars, W_r (ton), Q is the maximum plant discharge (m^3/s), L is the total length of open channel (m), B is the width of open channel (m), H is the height of open channel (m) and t is the concrete thickness (m), 1 m.

Assumptions

The specifications of tailrace tunnel for some power plants are described in Table 3.10 in Chapter 3. For the power plants those tailrace types and specifications are unknown, it is assumed the tailrace channel types. Hence, if the total length of the open channel – L (m) is unknown, it can be calculated by following steps by using Equation (5.68).

$$V_{c-plant} = \frac{V_{c-Ann} \times Q_{plant}}{Q_{Ann}} \tag{5-68}$$

Where $V_{c\text{-}plant}$ is the concrete volume used at the specific power plant, $V_{c\ Ann}$ is the concrete volume of Ann project, 374 m^3, Q_{plant} is the maximum plant discharge m^3/s, Q_{Ann} is the maximum plant discharge of Ann project, m^3/s, 44.00m^3/s (Mizuta & Takeda, 2015). From Equation (5.68), $V_{c\text{-}plant}$ is calculated first. After calculating the concrete volume of the specific power plant, the total length of open channel, L can be calculated from Equation (5.66) by using the value of $V_{c\text{-}plant}$, the concrete thickness, t, the width of the open channel, B and the height of the open channel, H those are calculated from Equations (5.63), (5.64) and (5.65).

(9) Tailrace Outlet

The work quantities for tailrace outlet can be calculated by Equations (5.69), (5.70) and (5.71).

$$V_e = 395 \times (R \times q)^{0.479} \times n \tag{5-69}$$

$$V_c = 40.4 \times (R \times q)^{0.684} \times n \tag{5-70}$$

$$W_r = 0.278 \times V_c^{0.610} \times n \tag{5-71}$$

Where, q is the design discharge (m^3/s) which is equivalent to the maximum plant discharge when the waterway has only one channel, meaning (q = Q). Otherwise, If the waterway has n number, q is equivalent to the maximum plant discharge divided by n channel, (q = Q/n). R is the tunnel radius (m) and n is the number of waterway channels.

Assumptions

For all the hydropower plants, the volumetric flow rates at each turbine (to calculate the maximum plant discharge, Q) are described in Table 3.2 and Table 3.3 in Chapter 3. If R is unknown, the tunnel radius can be calculated by the same way as intake from Figure 5.2 by using Equations (5.25) and (5.26).

(10) Turbines and Generators

The turbines and generators data provided from MOEP have been described in Table 3.13 in Chapter 3. Hence, the weight of turbine and generator those rated capacity 20 MW will be used as a reference to calculate the turbine and generator weight for other power plants based on their rated capacity. For instance, each turbine rated capacity of Yeywa hydropower plant (790 MW) is 197.50 MW. Based on weight of the turbine and generator' rated capacity 20 MW shown in Table 3.13 in Chapter 3, turbine weight for Yeywa plant is estimated to be 1070450 kg and generator weight is estimated to be 2214963kg.

In this regard, turbine is made up of stainless steel 28% and structural steel 72% and generator is fabricated with copper 6%, structural steel 45% and steel sheet 49% (Arnøy & Modah, 2013). To figure out the embodied energy in those materials, the embodied energy (MJ/kg) values of steel (structural), steel (stainless), steel (plate) and copper (general) will be referenced as shown in Table 5.1.

5.3 Energy Payback Time (EPT)

The Energy Payback Time (EPT) is defined as the starting time of a specific power plant to deliver the energy surplus to the economy. It is also known as the time when the power plant start commissioning until it generates the same amount of energy it consumes to construct, maintain and operate within the life expectancy of the power plant. Otherwise, the specific power plant reaches the EROI value of 1 when energy investment amount are presented in chorological order (Atlason & Unnthorsson, 2014). Hence, the input of the power plant can be described as follows:

$$x\,(t) = a + (b + c)\ \times t \tag{5-72}$$

Where, x is the energy input over time (t), a is all the energy invested at the construction stage which includes the energy investment amount in all the construction materials, b is the maintenance amount of energy (the reinvestment energy is used in this study), c is the own consumption of the power plant over time (t). The output can be described as a function as follows:

$$y\,(t) = d.\,t \tag{5-73}$$

Where d is the energy output from the power plant, the energy payback time (EPT) is reached as the following condition:

$$y\,(t) = x\,(T) \tag{5-74}$$

Where T is the expected lifetime of the power plant whereas y is the output energy for the given time period (Atlason & Unnthorsson, 2014).

To calculate EPT in this study, the annual electrical output is divided by the total energy input account for maintenance, operation and construction within the life time of the power plant (Atlason & Unnthorsson, 2014).

5.4 EROI$_{stnd}$ Calculation for the Storage Type Hydropower Plants

A sample calculation of Kunn Chaung multipurpose hydropower plant (60 MW) is described in Appendix, in which the detailed discussion of project general information, Total Process Electrical Output calculation, Total Process Energy Input calculation, EROI$_{stnd}$ value and energy payback time (EPT) calculation by using the real data collected from MOEP and estimated data by all equations described in section 5.2 and 5.3. Similarly, the EROI$_{stnd}$ values of all storage type hydropower plants are calculated the same way as Kunn Chaung hydropower plant.

5.5 $EROI_{stnd}$ for Storage Type Hydropower Plants

5.5.1 $EROI_{stnd}$ Results for 47 Storage Type Hydropower Plants

In this study, it is noted that the $EROI_{stnd}$ value resulted from the specific power plant is defined as "high $EROI_{stnd}$ value" if a power plant delivers the energy surplus to the economy at the very first year of the plant is commissioned. Otherwise, the Energy Payback Time (EPT) of this power plant is reached when the power plant start commissioning until it generates the same amount of energy it consumes to construct, maintain and operate within the life expectancy of the power plant. This specific plant reaches the $EROI_{stnd}$ value of 1 when energy investment amount are presented in chorological order. Likewise, the $EROI_{stnd}$ value is defined as "low $EROI_{stnd}$ value" in this study if a power plant cannot deliver energy surplus to the society at the very first year of the plant is commissioned, meaning that the $EROI_{stnd}$ value of the plant is less than 1 at the very first year. The detailed discussion of EPT for the power plants is described in Section 5.5.5.

The projected $EROI_{stnd}$ values within the 100-year life time of each storage type hydropower plant are described in Table 5.3. Figure 5.5 (A) shows these results of $EROI_{stnd}$ values as ascending order and Figure 5.5 (B) describes these values are grouped based on different dam types. In Figure 5.5 (A), the red bars represent the results of 18 constructed, the green bars represent the results of 5 under-construction and the blue bars represent the results of 24 planned power plants, in total the $EROI_{stnd}$ results of 47 storage type hydropower plants, ranked in ascending order, from the smallest value, 2 to the highest value, 127.

Based on the results of this study, most of the constructed and under-construction hydropower plants have low $EROI_{stnd}$ values, except Yeywa (790 MW), Upper Yeywa (280 MW) and Chi Phwae Nge (99 MW). The $EROI_{stnd}$ results of those power plants are Yeywa (790 MW), 69, Upper Yeywa (280 MW), 69 and Chi Phwae Nge (99 MW), 85 within their life expectancy. It is obvious that the energy returns from these power plants significantly goes into the society at the beginning of the plants commissioned because they have relatively high $EROI_{stnd}$ values. The $EROI_{stnd}$ values of some constructed hydropower plants such as Zawgyi 2 (12 MW), Thaphanseik (30 MW), Saedawgyi (25 MW) and Zaungtu (20 MW) are very low; lower than 10 within 100-year life time, meaning the less energy is available to the society since the beginning of the plants commissioned. However, the rest of the constructed and under-construction power plants have fair $EROI_{stnd}$ values, resulted in the values between 10 and 50, reflecting the considerable amount of energy return to the society.

When the $EROI_{stnd}$ values of the planned power plants are considered, most of the planned power plants have high $EROI_{stnd}$ values. Therefore, it is obvious that the large amount of energy surplus from those power plants can be significantly provided to the society rather than the constructed and under-construction power plants. Among 24 planned power plants, 9 power plants namely, Hutgyi (1360 MW), Maingtong (7000 MW), Khaunglanphuu (2700 MW), Wusauk (1800 MW), Laizar (1900 MW), Naung Pha (1200 MW), Ywathit (4000 MW), Phizaw (2000 MW) and Kunlong (1400 MW) have the highest $EROI_{stnd}$ values, 103, 103, 110, 117, 117, 117, 124, 124 and 127.

Table 5.3 Projected $EROI_{stnd}$ values of storage type hydropower plants.

No.	Projects	$EROI_{stnd}$	GWh/y	Dam Type
1	Zawgyi 2	2	30	Gravity Dam
2	Thaphanseik	3	117	Homogeneous Earth-Fill Dam
3	Saedawgyi	6	134	Composite Dam
4	Zaungtu	8	76	Homogeneous Earth Fill Dam
5	Khabaung	10	120	Homogeneous Earth-Fill Dam
6	Yenwe	13	123	Zone Type Earth-Fill Dam
7	Phyuu Chaung	14	120	Zone Type Earth-Fill Dam
8	Shwegyin	14	262	Zone Type Rock-Fill Dam
9	Thahtay	14	386	Zone Type Rock-Fill Dam
10	Kinda	16	165	Zone Type Rock-Fill Dam
11	Mone	18	330	Zone Type Earth-Fill Dam
12	Upper kengtaung	18	267	Zone Type Rock-Fill Dam
13	Upper Paunglaung	19	454	Roller Compacted Concrete Dam
14	Nan Cho	23	152	Gravity Dam
15	Kunn Chaung	24	190	Zone Type Earth-Fill Dam
16	Kyeeohn Kyeewa	30	370	Zone Type Rock-Fill Dam
17	Paunglaung	34	911	Zone Type Rock-Fill Dam
18	Shweli 3	34	3400	Roller Compacted Concrete Dam
19	Xo Luu	35	775	Concrete Faced Rock-Fill Dam
20	Manipour	43	1903	Zone Type Rock-Fill Dam
21	Thaukyaekhat 2	47	604	Concrete Faced Rock-Fill Dam
22	Middle Paunglaung	49	500	Gravity Dam
23	Maing Wah	54	274	Gravity Dam
24	Mantaung	55	992	Concrete Faced Rock-Fill Dam
25	Wun Tar Pin	62	170	Gravity Dam
26	Yeywa	69	3550	Roller Compacted Concrete Dam
27	Upper Yeywa	69	1409	Roller Compacted Concrete Dam
28	Kengtong	75	655	Concrete Faced Rock-Fill Dam
29	Keng Yang	77	204	Gravity Dam
30	Chi Phwae Nge	85	599	Concrete Faced Rock-Fill Dam
31	Shweli 2	85	2814	Gravity Dam
32	Gawlan	91	594	Gravity Dam
33	Chi Phwae	92	17770	Roller Compacted Concrete Dam
34	Tongxinqiao	93	1695	Gravity Dam
35	Khankan	93	642	Gravity Dam
36	Dapein 2	97	769	Concrete Faced Rock-Fill Dam
37	Yee Nan	97	6182	Gravity Dam
38	Longdin	98	2800	Concrete Faced Rock-Fill Dam
39	Hutgyi	103	7325	Roller Compacted Concrete Dam
40	Maingtong	103	34717	Roller Compacted Concrete Dam
41	Khaunglanphuu	110	14730	Concrete Faced Rock-Fill Dam
42	Wusauk	117	10140	Concrete Faced Rock-Fill Dam
43	Laizar	117	10440	Concrete Faced Rock-Fill Dam
44	Naung Pha	117	6650	Roller Compacted Concrete Dam
45	Ywathit	124	21789	Roller Compacted Concrete Dam
46	Phizaw	124	11080	Concrete Faced Rock-Fill Dam
47	Kunlong	127	7142	Gravity Dam
	Total		**176521**	

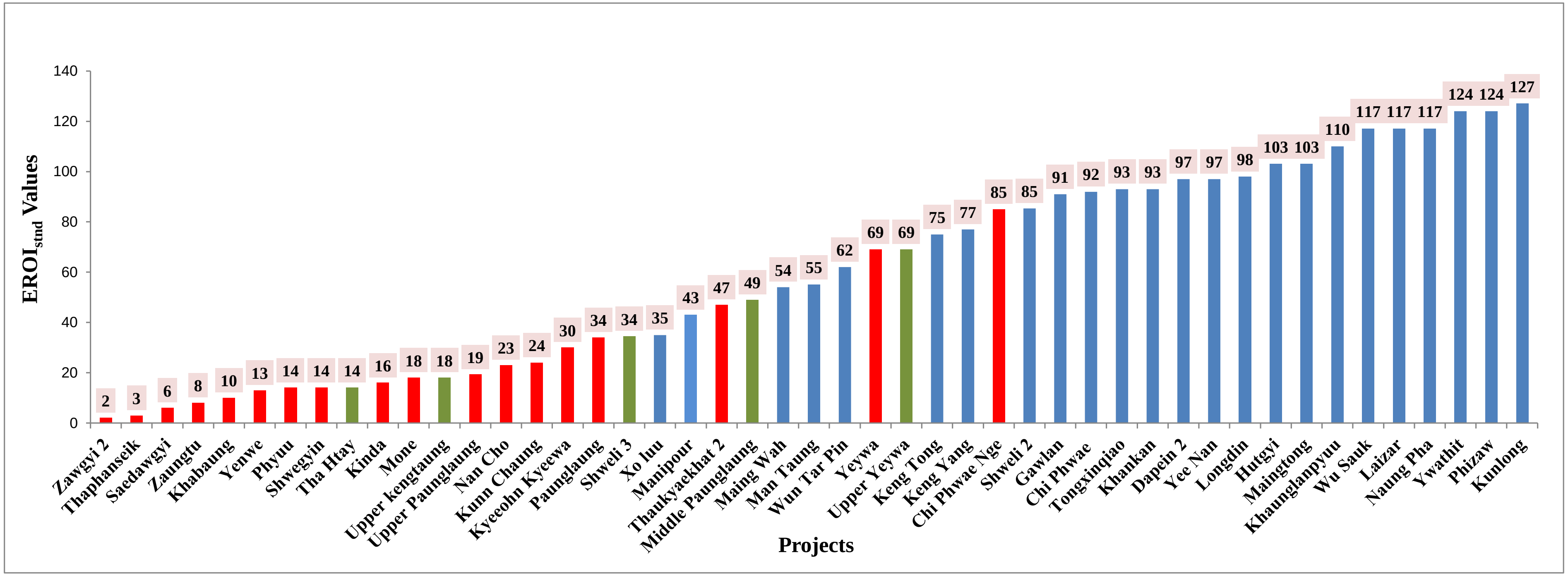


Figure 5.5 (A) Projected EROI$_{stnd}$ values of storage type hydropower plants.

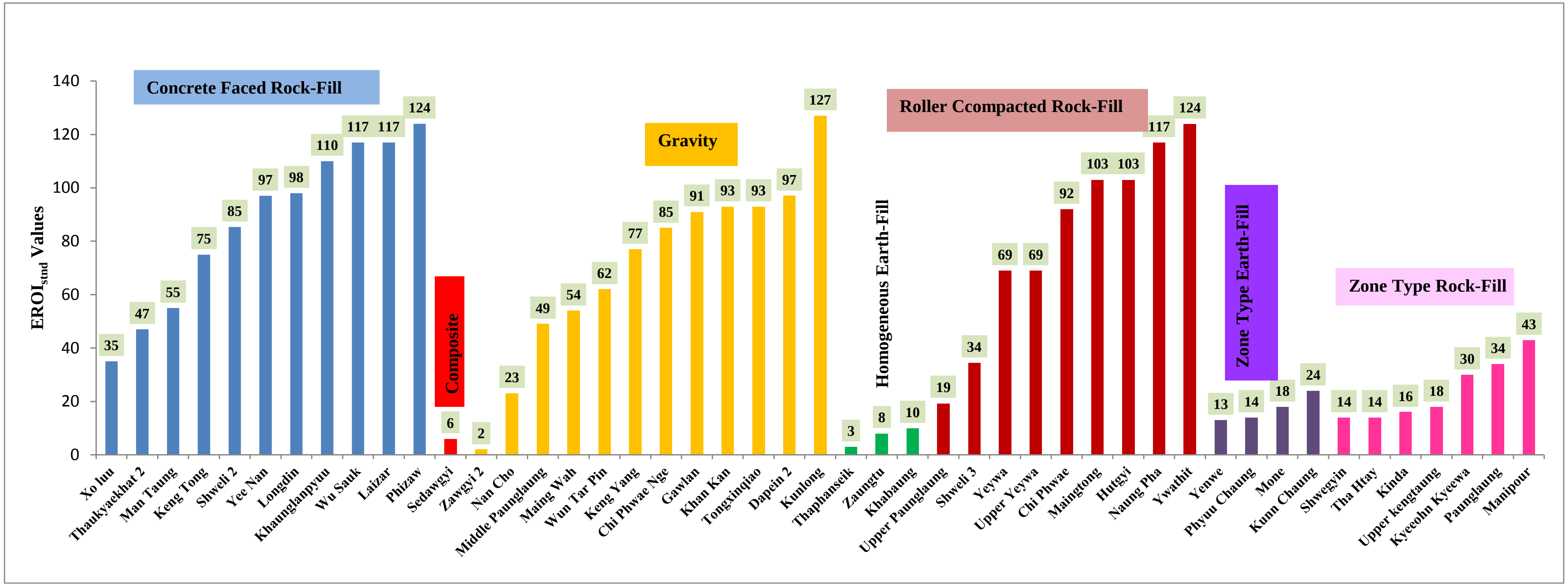


Figure 5.5 (B) Projected EROI$_{stnd}$ values relative to different dam types.

5.5.2 Correlation Analysis between $EROI_{stnd}$ Values and Annual Energy Generation (GWh/y) or Installed Capacity (MW)

As the general concept of the ratio of EROI is the energy output and energy input, the analysis of the correlation between the results of $EROI_{stnd}$ values and annual energy generation (GWh/y) or installed capacity (MW) of the power plants are figured out. Figure 5.6 illustrates the relationship between the $EROI_{stnd}$ values and annual energy generation (GWh/y) whereas Figure 5.7 shows the correlation between the $EROI_{stnd}$ values and installed capacity (MW) for 47 storage type hydropower plants. Both figures illustrates that there is a moderately positive correlation between the $EROI_{stnd}$ values and annual energy generation (GWh/y) or installed capacity (MW). Thus, the larger values of the power plants' annual energy generation or installed capacity are associated with the larger values of the $EROI_{stnd}$ values of those power plants. As the explanatory variables of annual energy generation or installed capacity increases, the response variables of the power plants, the $EROI_{stnd}$ values increases or vice versa the fact that both variables move into the same direction with the linear relationship (Minitab, 2016).

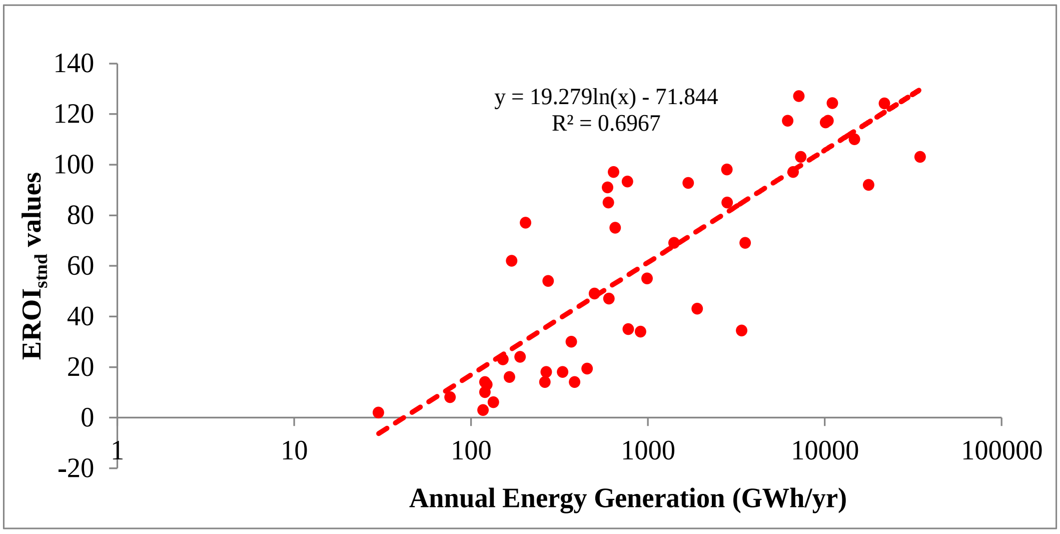


Figure 5.6 EROI$_{stnd}$ values vs. annual energy generation.

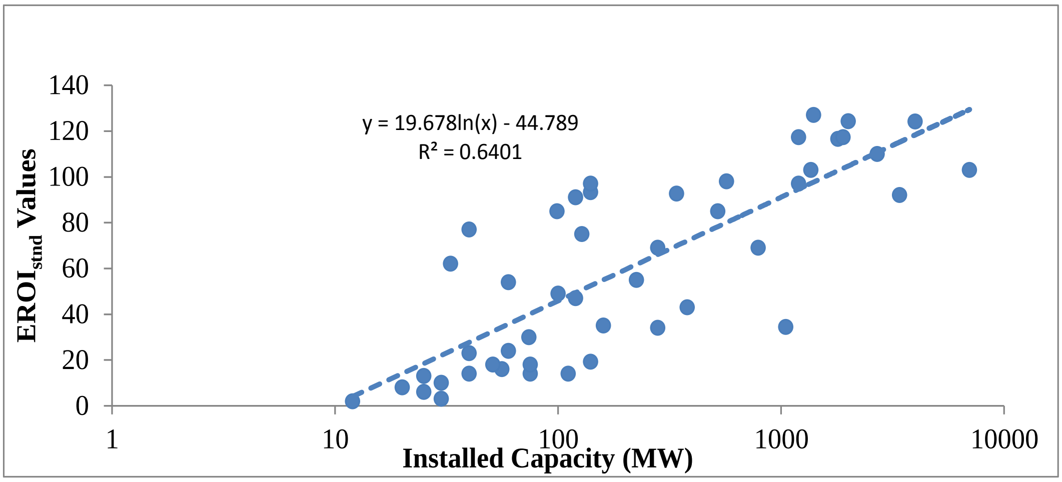


Figure 5.7 EROI$_{stnd}$ values vs. installed capacity.

5.5.3 Correlation Analysis between EROI$_{stnd}$ Values and Capacity Factor

Figure 5.8 illustrates the relationship between the EROI$_{stnd}$ values and capacity factor for 47 storage type hydropower plants, in which the horizontal (explanatory) variable, capacity factor range from the smallest 0.29 to the largest, 0.69 and the vertical (response) variable, the EROI$_{stnd}$ values range from the lowest, 2 to the highest, 127. The capacity factor data for all power plants are described in Table 3.4 and 3.5 in Chapter 3. There is a moderately positive correlation between the EROI$_{stnd}$ values and capacity factor of the power plants. This relationship point out that the larger values of the capacity factor are associated with the larger values of the EROI$_{stnd}$ values.

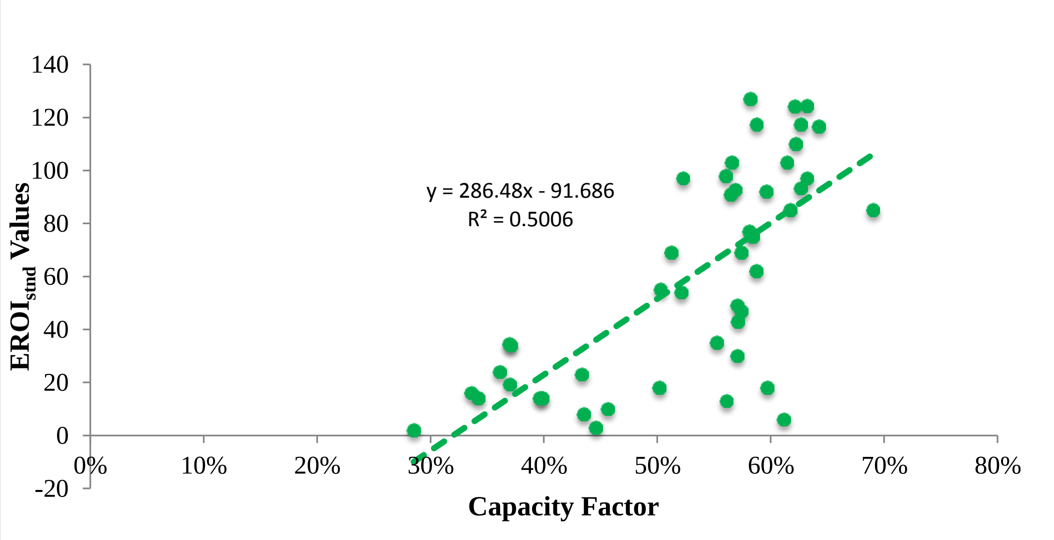


Figure 5.8 EROI$_{stnd}$ values vs. Capacity Factor.

5.5.4 Analysis of the Relationship between EROI$_{stnd}$ Values and Dam Volumes of Different Dam Types

As the massive dam volumes of the different dam types can be the largest amount of embedded energy in Total Process Energy Inputs, the correlation between the EROI$_{stnd}$ values and the dam volumes for different dam types is figured out. In Figure 5.9, the explanatory variables, the respective dam volumes for 7 different dam types, those range from the smallest dam, 25965 m^3 to the largest dam, 27006282 m^3, in which the dam volume of the Conventional Vibrated Concrete (CVC) Gravity dam types are generally smaller than the massive Fill dam types. However, Roller Compacted Concrete (RCC) dams which consist of gravity dam types, their volume are also massive depending on the necessities of the work quantities. The response variables, the EROI$_{stnd}$ values range from the lowest, 2 to the highest, 127. It is apparently seen that there is a nearly zero correlation between the EROI$_{stnd}$ values and the dam volumes regardless of dam volumes and dam types due to the fact that the two sets of variables have no association with each other.

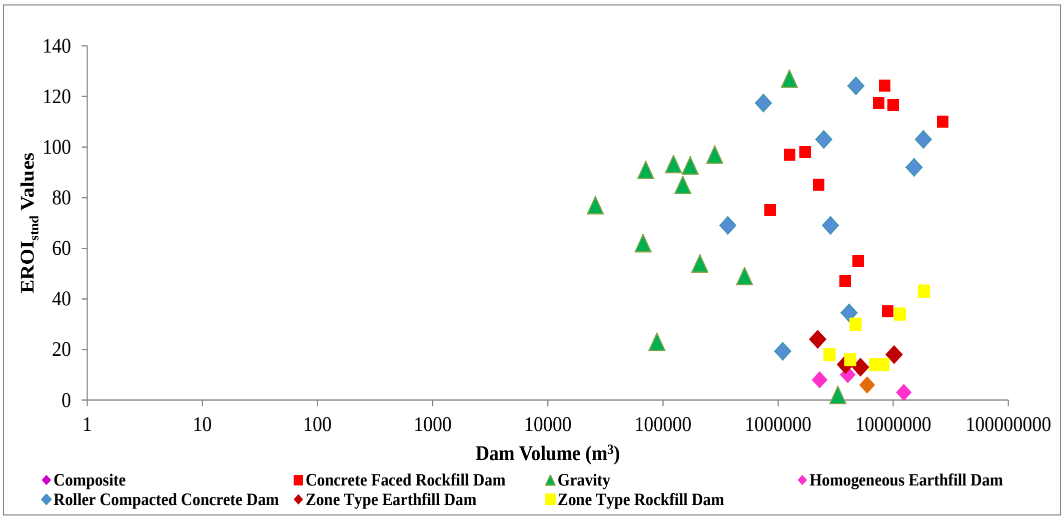


Figure 5.9 $EROI_{stnd}$ values vs. dam volume.

5.5.5 Results Concerning Energy Payback Time (EPT)

As was done for Kunn Chaung multipurpose hydropower plant, the Energy Payback Time (EPT) values are calculated for 47 storage type hydropower plants using the Equations (5.72), (5.73) and (5.74) described in Section 5.3. Figure 5.10 illustrates the different energy payback time EPT results for 23 constructed and under-construction hydropower plants, whereas Figure 5.11 depicts EPT results for 24 planned hydropower plants.

As Energy Payback Time (EPT) is the ratio of the annual electrical output to the total energy input account for maintenance, operation and construction within the life time of the power plant, the EPT values are described from the very first year up to the end of the plant lifetime, 100 years. As illustrated in Figure 5.10, the Energy Payback Time (EPT) for most of the constructed and under construction power plants are longer than one year except Chi Phwae Nge (99 MW), Yeywa (790 MW) and Upper Yeywa (280 MW). These three power plants have the significant energy payback time, in which the $EROI_{stnd}$ values at plants' first commissioned year are 1.79, 1.13 and 1.21 respectively. Therefore, the energy surpluses from those power plants are returned to the society since those plants have been commissioned at the first year and the generated energy from those power plants can provide a highly significant energy return to the society from the whole life expectancy due to the fact that the energy return are higher than the invested energy annually. The energy payback time for the rest of the power plants have less than a year, in which EPT of some power plants have less than 1 year, but the energy return can get back after second or third or fourth up to seven year operation. However, the energy payback time for some power plants such as Zawgyi 2 (12 MW), Thaphanseik (30 MW) and Sedawgyi (25 MW), Zaungtu (20 MW) and Khabaung (30 MW) have more than 10 years. The reason is these power plants have low annual energy generation and high embedded energy in the massive dam volumes resulted in the low energy payback time.

Figure 5.11 depicts the energy payback time for 24 planned power plants within their life expectancy. On this account, the $EROI_{stnd}$ values for all the power plants are more than 1 at the beginning of the power plants' life time except Xo Luu (160 MW), Manipour (380 MW), Maing Wah (60 MW) and Mangtaung (225 MW). Apart from these four power plants, all the planned power plants have high EPT since the first year of the power plants' commissioned. Hence, the energy payback time for those power plants is very high even at the first year of the plant operation, from 1.24 to 4.51 due to the significant high annual energy generation of the power plants. It means that for every 1 unit of energy invested for the power plant, the energy is returned from 1.24 to 4.51 fold back into the society. The energy payback time for Xo Luu (160 MW), Manipour (380 MW), Maing Wah (60 MW) and Mangtaung (225 MW) have longer than 1 year, but the energy return can get back after two or three years operation.

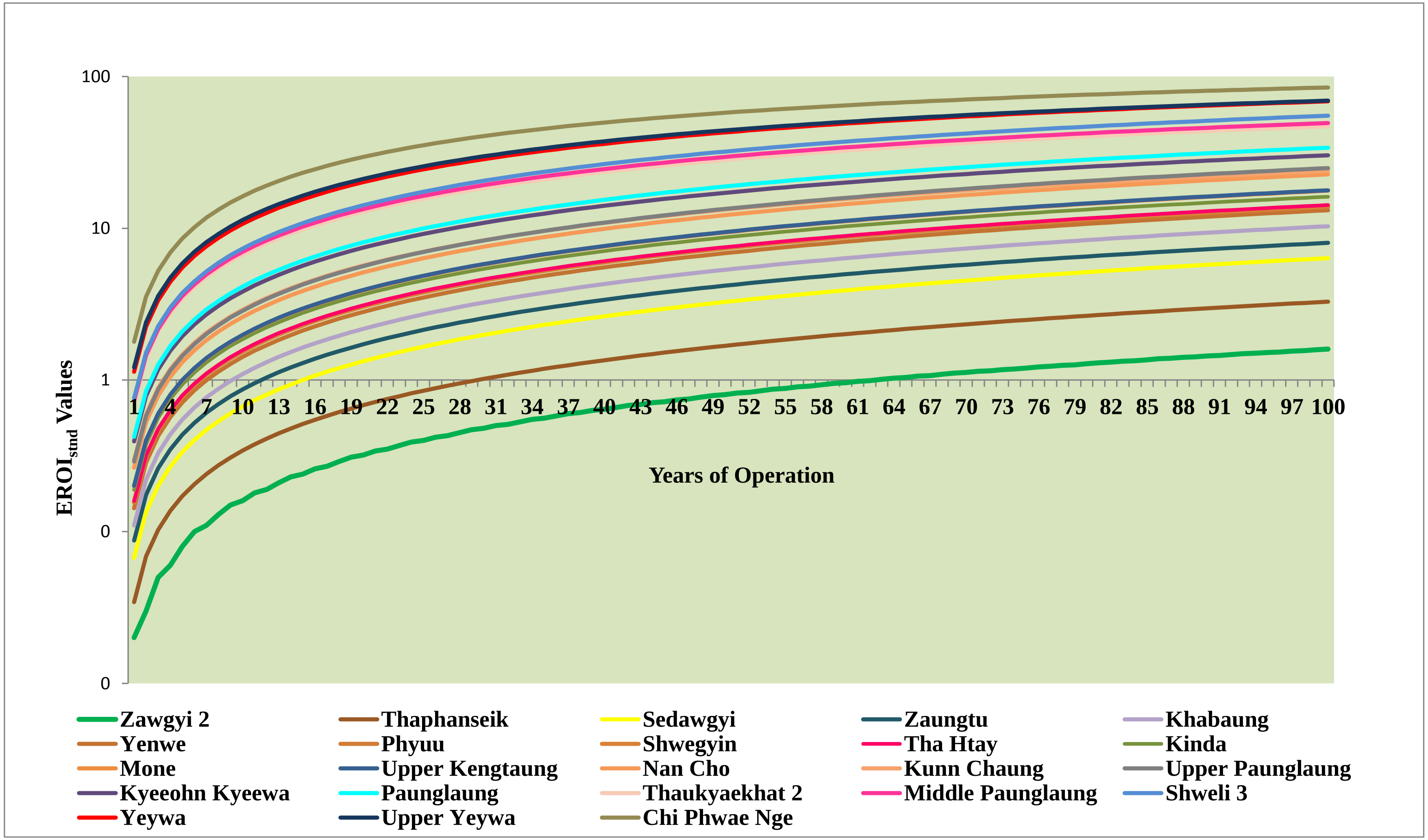


Figure 5.10 Energy Payback Time for constructed and under-construction power plants.

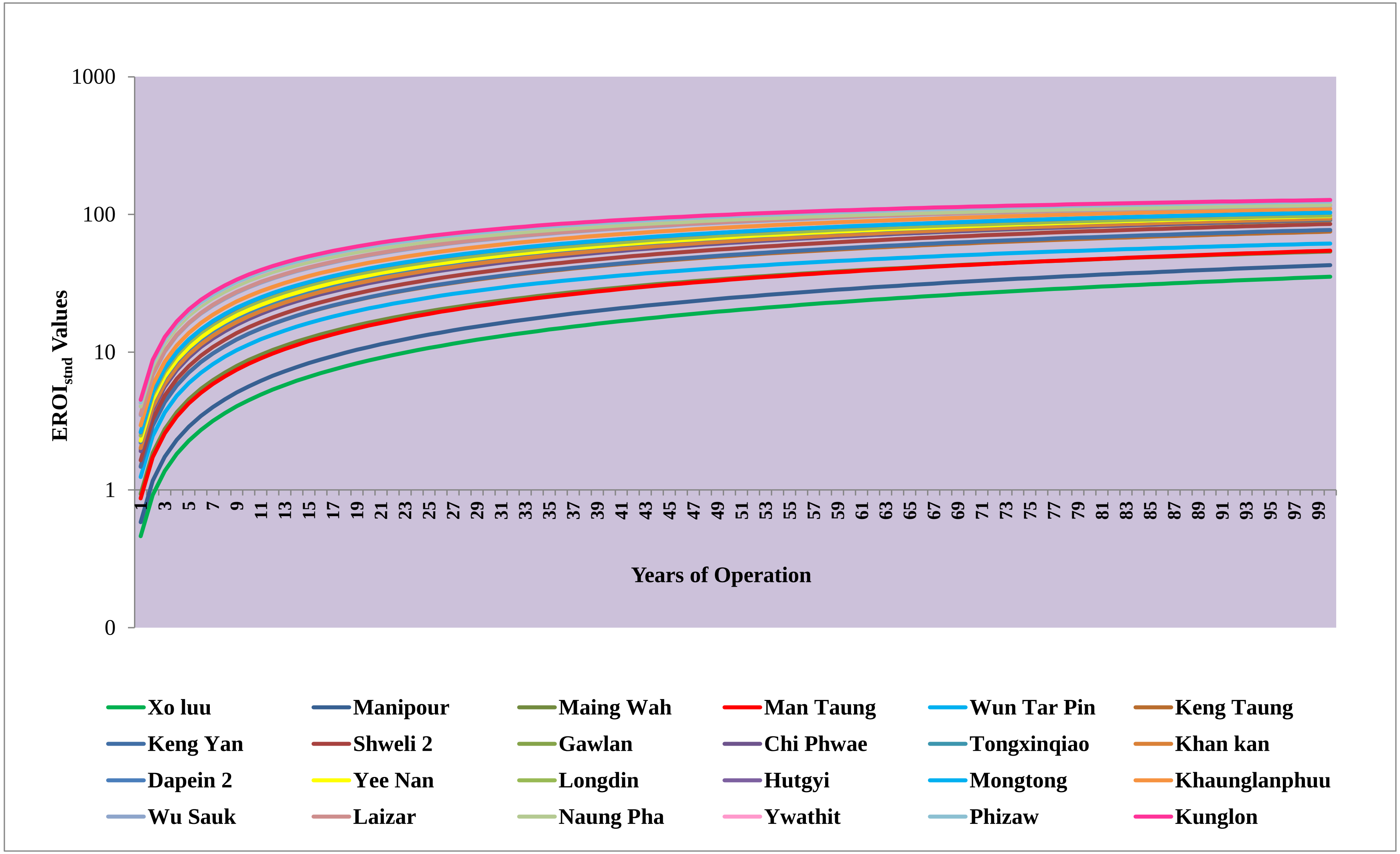


Figure 5.11 Energy Payback Time (EPT) for planned power plants.

5.6 Discussions

Based on the $EROI_{stnd}$ results, the following reasons are discussed as a brief explanation which influences on the $EROI_{stnd}$ values:

1. The high $EROI_{stnd}$ values of the power plants are concerned with the hydropower plants' annual energy generation (GWh/y) in terms of the Total Process Electrical Output of each power plant within their life expectancy. The power plants which have either high head (head higher than 300 m) or high volumetric flow rate (flow rate higher than 70 m^3/s at each turbine), they generate high annual energy, generally resulted in high $EROI_{stnd}$ values. Among 47 hydropower plants, 9 planned power plants namely Hutgyi (7325 GWh/y), Maingtong (34717 GWh/y), Khaunglanphuu (14730 GWh/y), Wusauk (10140 GWh/y), Laizar (10440 GWh/y), Naung Pha (6182 GWh/y), Ywathit (21789 GWh/y), Phizaw (11080 GWh/y) and Kunlong (7142 GWh/y) have the highest $EROI_{stnd}$ values, range from 103 to 127 as shown in Figure 5.5. In addition, the constructed hydropower plants such as Chi Phwae Nge (599 GWh/y) and Yeywa (3550 GWh/y), and under-construction hydropower plant, Upper Yeywa (1409 GWh/y), those power plants have also high $EROI_{stnd}$ values, 85, 69 and 69 respectively as shown in Figure 5.5. It is found out that the power plants which have high $EROI_{stnd}$ values have either high volumetric flow rate at each turbine or high head as shown in Table 3.2 and 3.3 in Chapter 3. Moreover, 11 planned power plants, namely Wun Tar Pin (170 GWh/y), Keng Tong (655 GWh/y), Keng Yan (204 GWh/y), Shweli 2 (2814 GWh/y), Gawlan (594 GWh/y), Chi Phwae (17770 GWh/y), Tongxinqiao (1695 GWh/y), Khankan (642 GWh/y), Dapein 2 (769 GWh/y), Yee Nan (6182 GWh/y) and Longdin (2800 GWh/y), those power plants have also high $EROI_{stnd}$ values, range from 62 to 98 as shown in Figure 5.5. Most of the 11 hydropower plants have either high volumetric flow rate at each turbine or high head as shown in Table 3.2 and 3.3 in Chapter 3, in which 3 planned power plants namely, Keng Tong (655 GWh/y), Gawlan (594 GWh/y) and Khankan (642 GWh/y) have medium head and medium volumetric flow rate (m^3/s). The Energy Payback Time (EPT) of those power plants is the very beginning of the lifetime, meaning that the power plants generate the significant amount of energy surplus at the first year since the plants commissioned.

2. As shown in Figure 5.5, the rest of 16 constructed, 4 under-construction and 4 planned hydropower plants have low $EROI_{stnd}$ values, from the highest, 55 to the lowest, 2. Among those power plants, some power plants have high volumetric flow rate and medium head, resulted in high annual energy generation such as Paunglaung (911 GWh/y), Kyeeohn Kyeewa (370 GWh/y), Thaukyaekhat 2 (604 GWh/y), Upper Paunglaung (454 GWh/y), Upper Kengtaung (267 GWh/y), Middle Paunglaung (500 GWh/y), Thahtay (386 GWh/y), Shweli 3 (3400 GWh/y), Xo Luu (775 GWh/y), Mantaung (992 GWh/y) and Manipour (1903GWh/y) power plants. Although the Energy Payback Time (EPT) of those power plants is not the first year, they can generate the surplus energy since second year or third year or fourth year or fifth year. Apart from those plants, the rest of the power plants which have low flow rate and either medium or low head, resulted in low annual energy generation. The Energy Payback Time for those power plants is longer than five years, in some cases, a very low amount of energy surplus return to the society.

3. Although it is generally assume that the power plants which have high annual energy generation can be resulted in high $EROI_{stnd}$ values, a few exceptional case are found out in this study. On this account, the power plants can have high $EROI_{stnd}$ values although the annual energy generations are not too high the fact that low energy investment in the energy inputs. For instance, the $EROI_{stnd}$ values of 3 planned power plants namely, Maing Wah (274 GWh/y), Keng Yan (204 GWh/y) and Wun Tar Pin (170 GWh/y) resulted in 54, 77 and 62 because of the considerable amount of the embedded energy in their gravity dam types leading to the high $EROI_{stnd}$ values. Moreover, the $EROI_{stnd}$ value cannot be the highest even though the power plant has highest annual energy generation (GWh/y) if it is considered each specific power plant. For instance, Maingtong (34717 GWh/y) is the highest annual energy generation among 47 power plants. However, the $EROI_{stnd}$ values of Kunglon (7142 GWh/y) is the highest, 127 because of the different energy invested in Total Process Energy Inputs.

4. In terms of the Total Process Energy Inputs perspective, power usage at site (if the plant has high annual energy generation), maintenance (if the electro-mechanical equipment' mass are much), transportation (for only RCC dam types due to RCC are transported from the factory which is far from the plant sites),

ground work phase (due to the massive volume of the dam) and construction stage (due to the massive volume of the dam) are considered as the stages which have high embedded energy among the eight parts of energy inputs. Otherwise, preparation stage, hydraulic equipment and electro-mechanical equipment are considered as the low energy usage parts based on the results of this study. In some cases, the percentage of the operational energy of the hydropower plants those have high annual energy generation is embedded as the highest in the Total Process Energy Inputs although the own consumptions is approximated 0.5 % of each year. For instance, Kunlong power plant has the highest $EROI_{stnd}$ values, 127 over 100 year of the plant life time. The annual energy generation of the plant is 7142 GWh/y, resulted in the Total Process Electrical output 2.57E+12 MJ within 100 years lifetime. This causes the own consumption 1.29E+10 MJ, if it is approximated to be 0.5% of its annual electricity production. The Total Process Energy Input of Kunnlong power plant is 2.02 E+10 MJ, in which the own consumption account for almost 63.72% of its total energy inputs, followed by the energy used at the construction stage 15.37 % and maintenance 8.76 % are included as the highest energy usage parts as shown in Figure 5.12. The embedded energy in electro-mechanical equipment is 4.59%, groundwork phase 4.16 %, transportation 2.6 %, hydraulic equipment 0.74 % and preparation 0.06 %, those are accounted as the lowest energy consumption parts. Likewise, it is generally found out that the operational energy percentage is the highest among Total Process Energy Inputs for the power plants those have high annual energy generation. Figure 5.13 shows the relative energy distribution between different phases for Kunlong power plant within 100 year lifetime. It is obvious that the energy invested in the construction stage is not the highest consumer throughout the lifetime of the power plant because the own consumption of the power plant is very high. This similar energy distribution pattern is found in the power plants those have high annual energy generation.

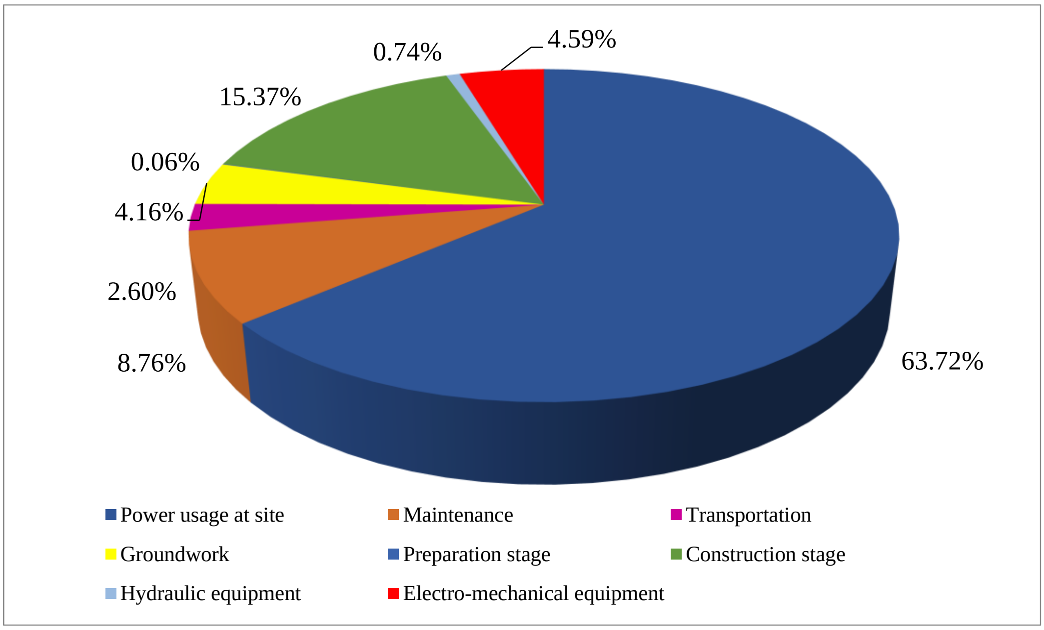


Figure 5.12 Embedded energy inputs percentage in Kunglong Power Plant.

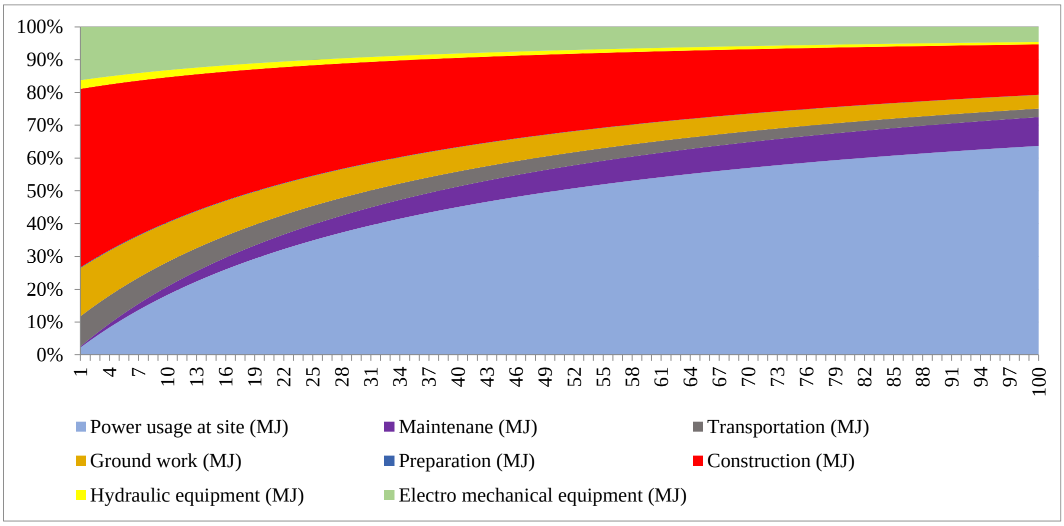


Figure 5.13 Relative energy distributions of Kunlong Power Plant.

5. In some cases, although the power plant has high annual energy generation, the operational energy percentage cannot be the highest because of the other reasons. For instance, the annual energy generation of Shweli 3 power plant is 3440 GWh/y. The dam type of this power plant is Roller Compacted Concrete (RCC) dam type; therefore, RCC materials are transported from the far distance from the plant site, resulted in the highest embedded energy usage at the transportation stage. In which, the embodied energy percentage in transportation stage is 40.39 %, followed by construction stage 23.14 %, operational energy 17.22 % and ground work phase 12.11 %. The rest of the energy percentage, totally 7.14 % represents the low energy usage group such as maintenance,

preparation, hydraulic and electro-mechanical equipment. Figure 5.14 shows the Total Process Energy Inputs percentage of Shweli 3 (1040 MW) power plant.

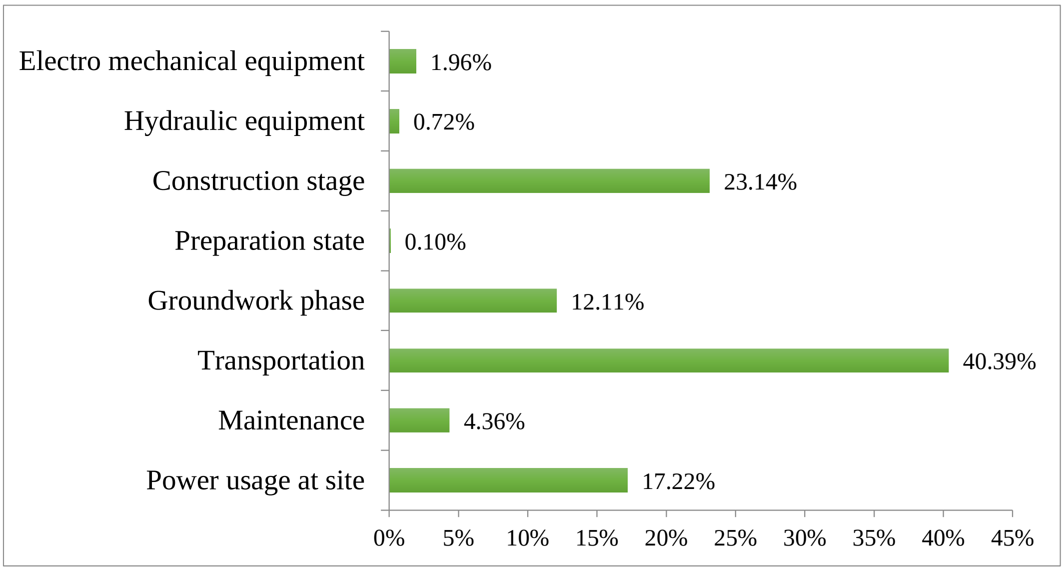


Figure 5.14 Total Process Energy Inputs percentage of Shweli 3 Power Plant.

6. The percentage of the embedded energy in dam volumes can be the highest in some cases despite the fact that the power plants have high annual energy generation, meaning the operational energy cannot be the highest. For instance, Paunglaung hydropower plant has high annual energy generation, 911 GWh/y. However, the energy used at the construction stage is the highest, due to the massive embedded energy in Zone Type Rock-Fill dam volume, 11480029 m^3, 47% followed by ground work 23%, operational energy 17%, and transportation 8%, and the rest of low energy percentage, totally 5% represents maintenance, preparation, hydraulic and electro-mechanical equipment.

7. As the energy expended at the construction stage can be the highest amongst the Total Process Energy Inputs, whereas the dam body can be the highest energy percentage among the construction stage for most of the power plants due to the massive embedded energy in their dam volumes. For instance, Zaungtu (20 MW) and Thaphanseik (30 MW) (Homogeneous Earth-Fill dams), Sedawgyi (25 MW) (Composite dam), and Zawgyi 2 (12 MW) (Gravity dam). For those power plants which have the massive dam volume and embedded energy in their dam body, the energy percentage in the dam body is the highest at the construction stage which can be ranged from 52% up to 90 % of the Total Process Energy Inputs. Figure 5.14 shows the energy distribution of Zaungtu (20 MW)

hydropower plant at the construction stage. Figure 5.15 shows the relative energy distribution between different phases for Zaungtu power plant within 100 year lifetime. It is obvious that the energy invested in the construction stage is the highest consumer throughout the lifetime of the power plant because the energy invested in dam body is very high. This similar energy distribution pattern is found in the power plants with high annual energy generation.

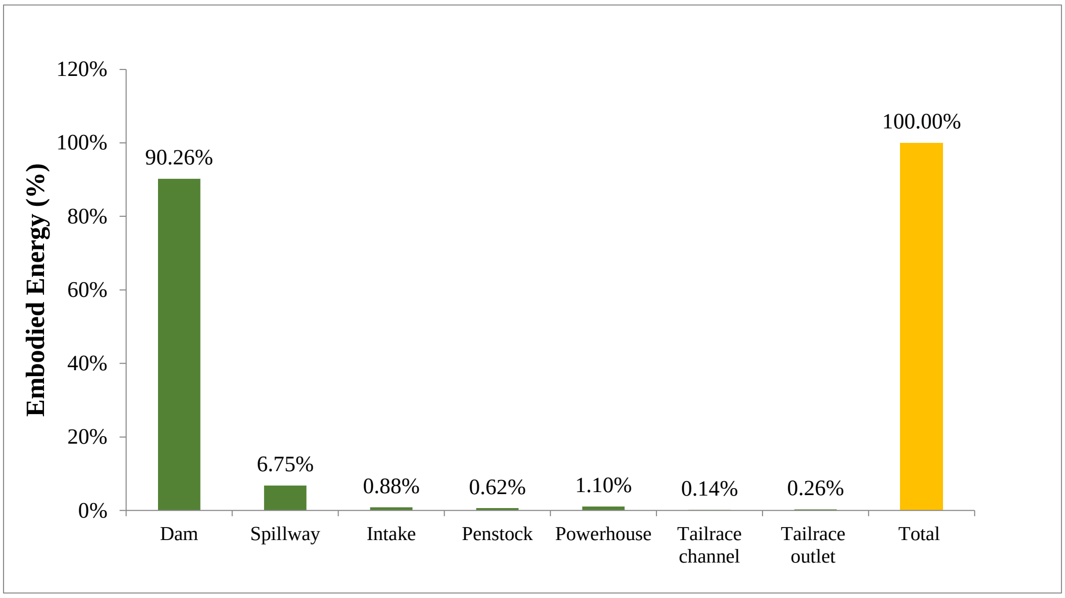


Figure 5.15 Highest embedded energy in dam body of Zaungtu (20 MW).

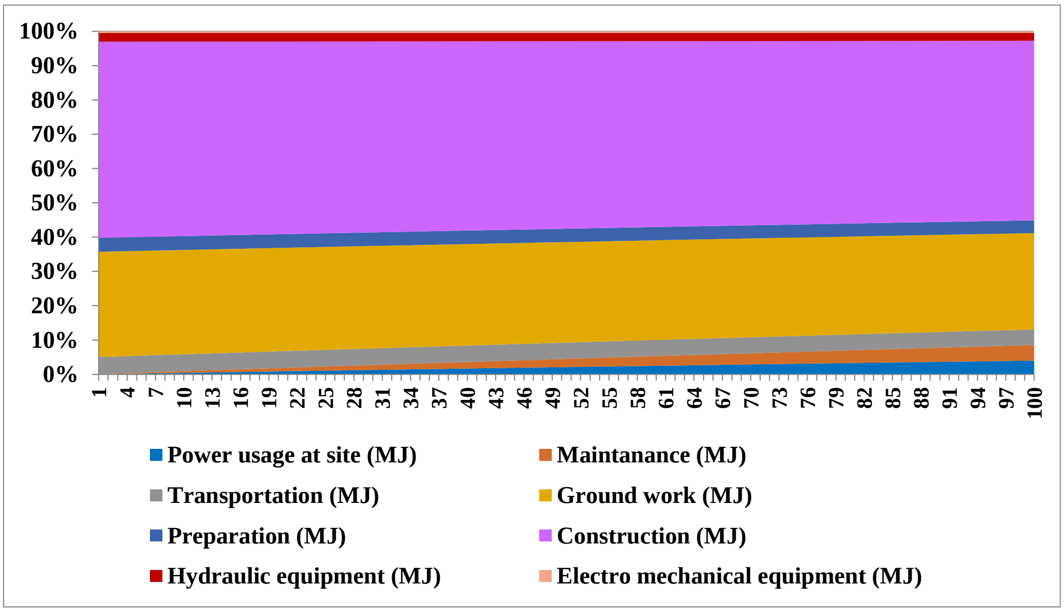


Figure 5.16 Relative energy distributions of Zaungtu (20 MW).

8. Generally, the embodied energy used in the construction stage of the plant can be the highest amongst other energy due to the massive volume of the dam. Hence, fill-dam volumes are generally much larger than the gravity dam volumes.

However, it does not mean the energy invested in fill-dam is greater than that of gravity dam in terms of the embodied energy (MJ) per unit mass (kg) according to their different dam types. Among seven different dam types, the Conventional Vibrated Concrete, CVC gravity dam has the highest embodied energy per unit mass 0.75 MJ/kg, followed by the Roller Compacted Concrete RCC dam, 0.66 MJ/kg, Composite dam, 0.44 MJ/kg, Homogeneous Earth-Fill dam, 0.36 MJ/kg, Zone Type Earth-Fill dam, 0.17 MJ/kg, Zone Type Rock-Fill dam, 0.15 MJ/kg and Concrete Faced Rock-Fill dam, 0.10 MJ/kg as shown in Figure 5.16. It should be noted that those embedded energy per unit mass values, (MJ/kg) are based on the materials percentage used in the dam volumes, the values can be differ if the materials percentage has been changed.

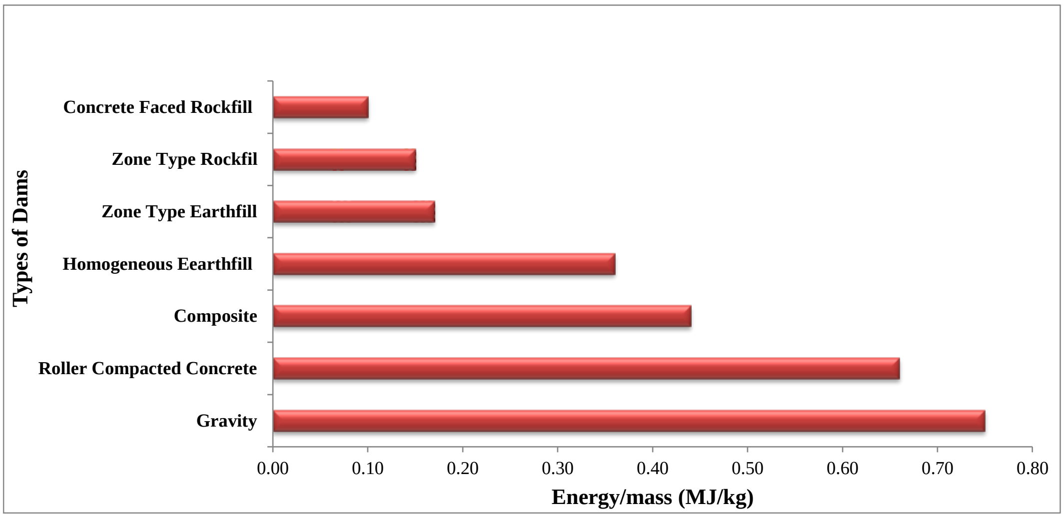


Figure 5.17 Energy expended per unit mass of different dam types.

The dam body makes the largest energy consumer of the construction stage in most cases; however, the other appurtenant structures can also be the highest energy consumer at the construction stage. For instance, Tongxinqiao (340 MW) uses a very long headrace tunnel with a length of 9700 m as one of the water conducting systems which is connected between the intake and the surge tank. A large amount of embedded energy percentage in the headrace tunnel resulted in the highest embodied energy percentage of the construction and ground work stage as shown in Figure 5.17. Likewise, in Longdin (570 MW), Khankan (140 MW) and Gawlan (120 MW) power plants, the embedded energy in headrace tunnels is the highest at the construction stage. Sometimes, the energy embedded in the penstock or spillways can be also the highest due to the large diameter and the length of penstock, and due to the large catchment area when calculating spillway work quantities in the Fill- dams type such as Kengtong (128 MW).

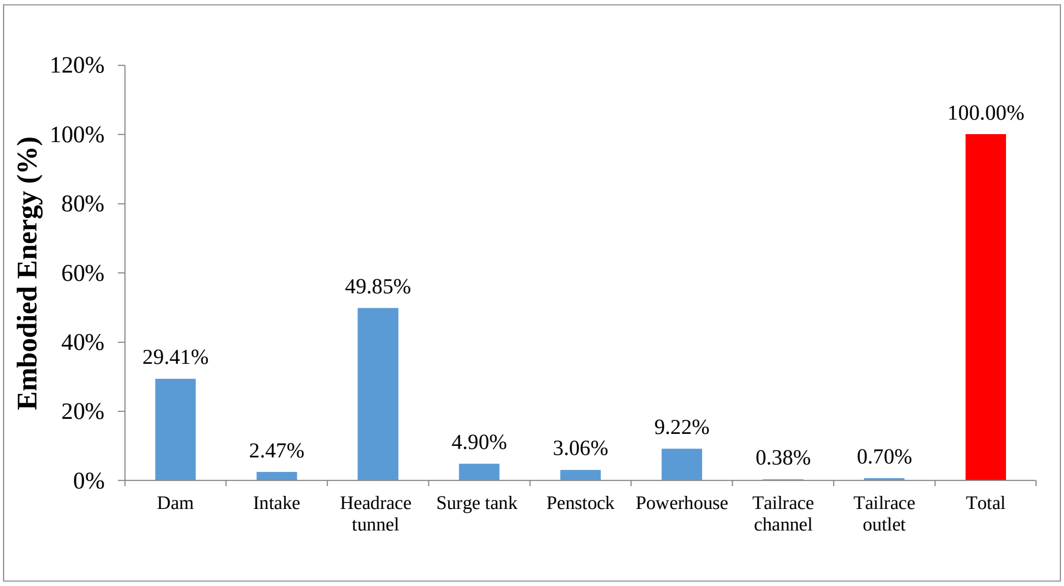


Figure 5.18 Highest embedded energy in headrace tunnel in Tongxinqiao (340 MW).

10. Own consumption and maintenance stage are likely to be the two most sensitive variables those can affect the $EROI_{stnd}$ values of the power plants (Atlason & Unnthorsson, 2014). In this regard, as the own consumption of all hydropower plants is estimated to be as 0.5 % of their annual energy generation, it can vary some years due to the instability of the plants energy consumption, it may be a little more one year, and also may be a little less one year that can be resulted in different $EROI_{stnd}$ values (Atlason and Unnthorsson, 2014). In terms of maintenance, only reinvestment energy amounted in the electro-mechanical equipment and hydraulic equipment are considered in this study. However, there would be some slight variations in the $EROI_{stnd}$ values if other elements are added as the energy inputs. Although these two stages are highly prioritized as the two possible variations, there may be some other underlying variables which can affect $EROI_{stnd}$ values in some cases. For instance, the embedded energy involvement at the preparation stage, if the energy embedded in the camp and facilities are counted, the energy invested in some civil work quantities such as grouting, coffering and saddle dams are counted. Since they have been ignored when calculating the Total Process Energy Inputs in this study and only the work quantities of the main items are considered according to predictive equations, the $EROI_{stnd}$ values can have slight changes because the values are sensitive to other additional energy inputs.

11. This study shows that some hydropower plants have very low $EROI_{stnd}$ values. For instance, Yenwe (25 MW), Khabaung (30 MW), Zaungtu (20 MW), Sedawgyi (25 MW), Thaphanseik (30 MW) and Zawgyi 2 (12 MW) power plants,

they have very low $EROI_{stnd}$ values, 13, 10, 8, 6, 3, 2. In that case, the reader may have a question regarding those very low $EROI_{stnd}$ values meaning that they can harness less energy than other power plants so they provide less energy to society than they consume. In addition, the Energy Payback Time (EPT) of those power plants is not the first year of the plants' commissioned, longer than one year. On this account, it should be notice that these power plants are constructed not only for electricity generation but also other purposes. These multipurpose power plants originally constructed for the irrigation and flood control purposes for the benefits of the society (Compendium, 2012). Even they generate less energy due to either low flow rate or low head according to their specific sites; they are still assisting the fruitful advantages for the society in terms of water supply purposes for many irrigated areas.

5.7 Conclusions

The storage type hydropower plants which can harness energy that have high $EROI_{stnd}$ values are more preferable than that of the power plants which have low $EROI_{stnd}$ values because they assist more energy surplus to the society since the beginning of the plants 'commission. This chapter calculated the $EROI_{stnd}$ values for 47 storage type hydropower plants in Myanmar by using the standardized methodology proposed by Murphy et al., 2011 and the predicative equations designed by Kansai Electric Power Co., Inc. This chapter confirms that the hydropower plants which have high annual energy generation can provide the better results of $EROI_{stnd}$ values approximately up to 127 during the plants life expectancy. It is obvious that every 1 unit of energy is used for the construction and operation of the power plants, the plants will return at least the range from 2 to 127 fold back into the society.

Chapter 6

Estimation of $EROI_{stnd}$ for Future Hydropower Generation in Myanmar

6.1 Introduction

The evaluated $EROI_{stnd}$ results have shown that the storage type hydropower plants that have high annual energy generation provide better energy return on the energy investment. This chapter examines how $EROI_{stnd}$ correlates to energy costs and energy production of storage type hydropower plants based on their different dam types. These correlations for estimating $EROI_{stnd}$ are then applied to planned storage type hydropower plants. By combining the best planned sites with current generation, the future energy expended by Myanmar electricity sector is predicted and the results are discussed.

6.2 Models for Estimation of $EROI_{stnd}$ for Hydropower Dams

The prediction of the relationship between the $EROI_{stnd}$ values and the ratio of "Energy Output" by "Energy Input" for different dam types are surmised using various models. As illustrated in Equation (6-1), the ratio of the $EROI_{stnd}$ values is generally expressed as Energy Output, E_{out} by Energy Input (Atlason & Unnthorsson, 2014), where the Energy Input is estimated using maintenance, operation, and dam volume with coefficients a_0 and b_0.

$$\mathrm{EROI_{stnd}} = \frac{\mathrm{E_{out}}}{\mathrm{a_0(Maintenence + Operation) + b_0(Dam\ Volume)}} \qquad (6\text{-}1)$$

Dam volume is a key dimension in determining the energy invested in materials transportation, ground work for dam site excavation and the dam construction. These three parts represent the largest contributors to total energy inputs. Other energy required for transportation of hydraulic and electro-mechanical equipment, fabrication, site preparation, and the spillway, intake, headrace tunnel, surge tank and tailrace, are relatively small and therefore not critical for predicting EROI.

Since the maintenance and operational energy are proportional to the energy output, Equation (6.1) can be rewritten with new coefficients a and b:

$$EROI_{stnd} = \frac{E_{out}}{a\,(E_{out}) + b\,(\text{Dam Volume})} \qquad (6\text{-}2)$$

Which may be to simplified to

$$EROI_{stnd} = \frac{1}{a + b \times (\frac{\text{Dam Volume}}{E_{out}})} \qquad (6\text{-}3)$$

And rearranged to

$$\frac{1}{EROI_{stnd}} = a + b\,(\frac{\text{Dam Volume}}{E_{out}}) \qquad (6\text{-}4)$$

By plotting $1/EROI_{stnd}$ against the ratio of Dam Volume by Energy Output (Eout) for 47 storage type hydropower plants, a straight line correlations is expected, from which coefficients a and b can be determined. From Figures 6.1 to 6.7, $1/EROI_{stnd}$ is plotted as the dependent variable on the Y-axis. The Dam Volume/E_{out} is plotted as the independent variable.

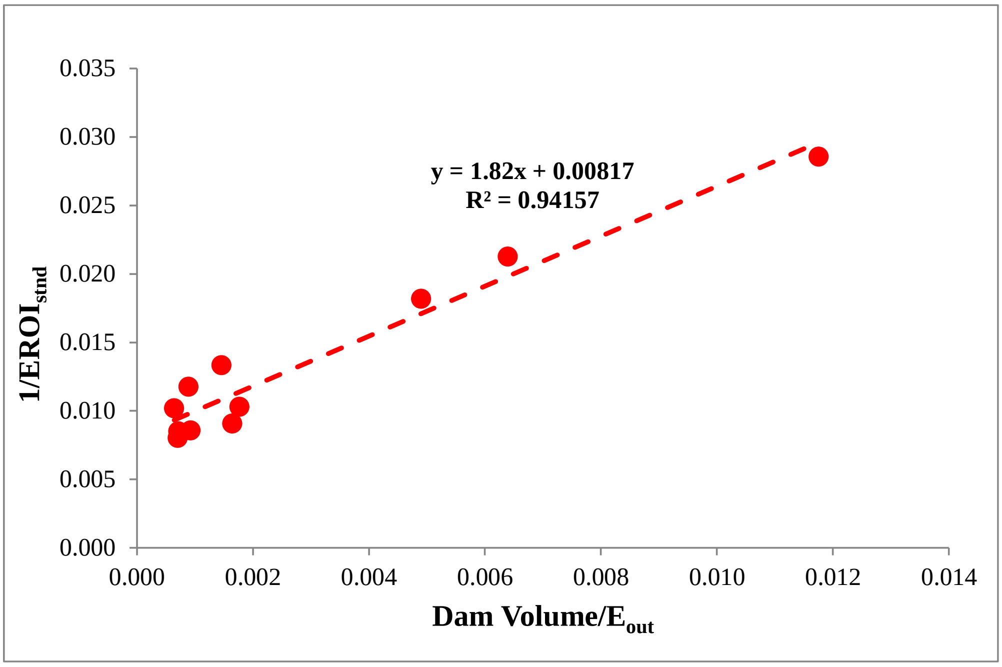


Figure 6.1 Relationship between $1/EROI_{stnd}$ and Dam Volume/Energy Output for Concrete Faced Rock-Fill Dams.

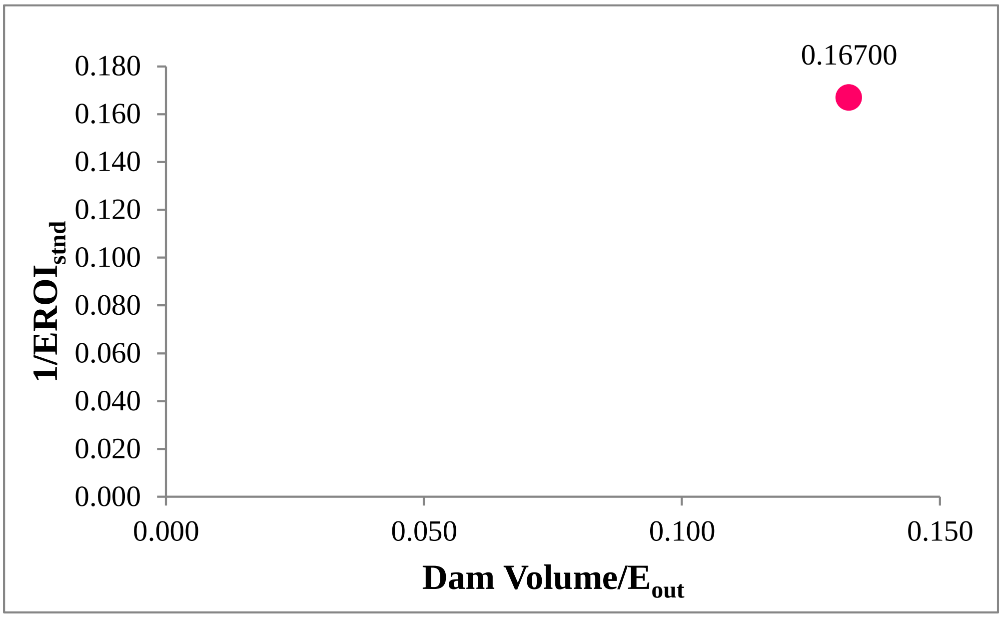


Figure 6.2 Relationship between 1/EROI$_{stnd}$ Value and Dam Volume/Energy Output for Composite Dam.

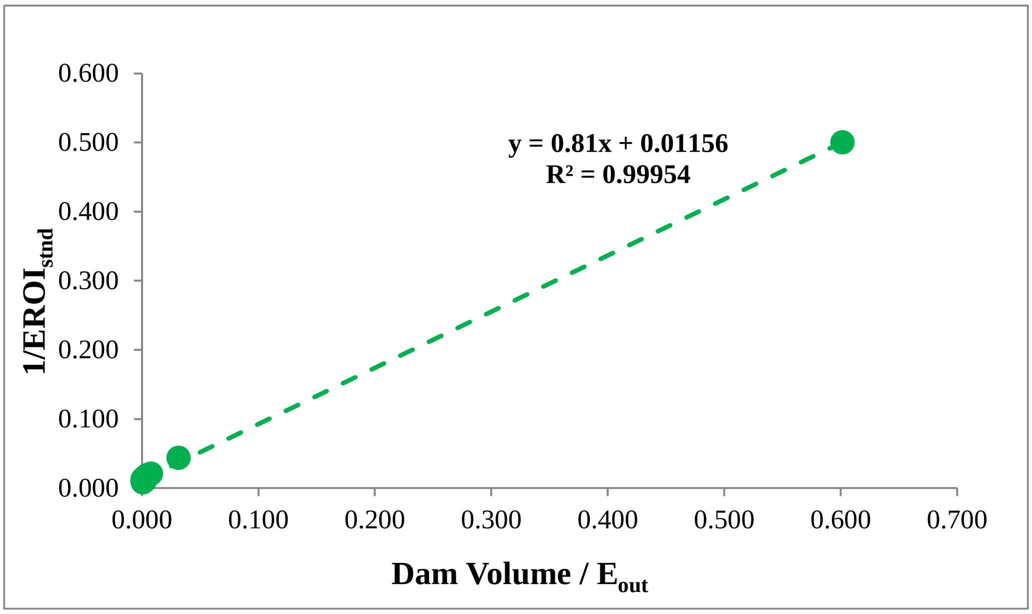


Figure 6.3 Relationship between 1/EROI$_{stnd}$ Values and Dam Volume/Energy Output for Gravity Dams.

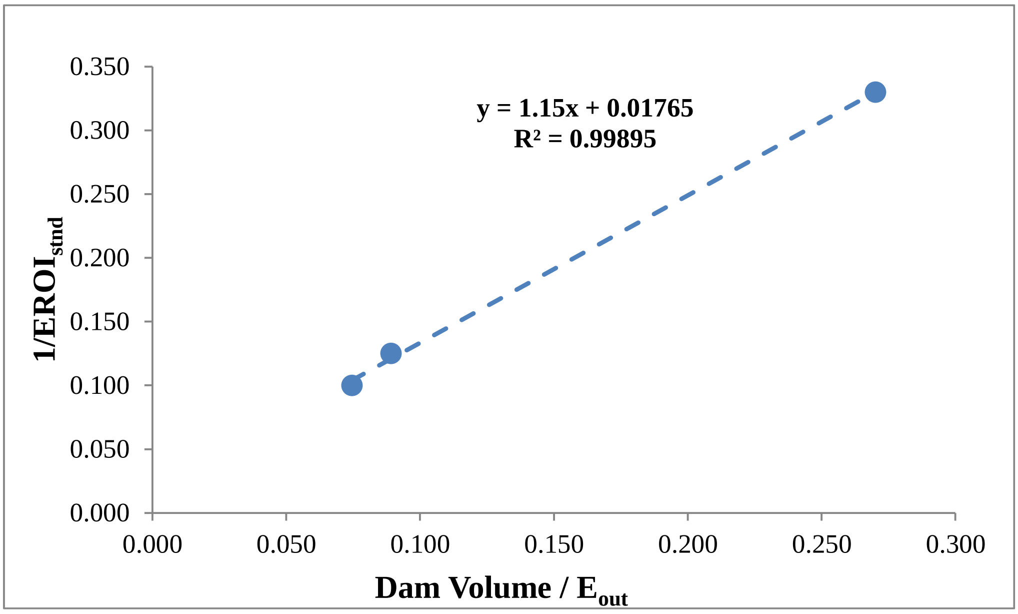


Figure 6.4 Relationship between 1/EROI$_{stnd}$ Values and Dam Volume/Energy Output for Homogeneous Earth - Fill Dams.

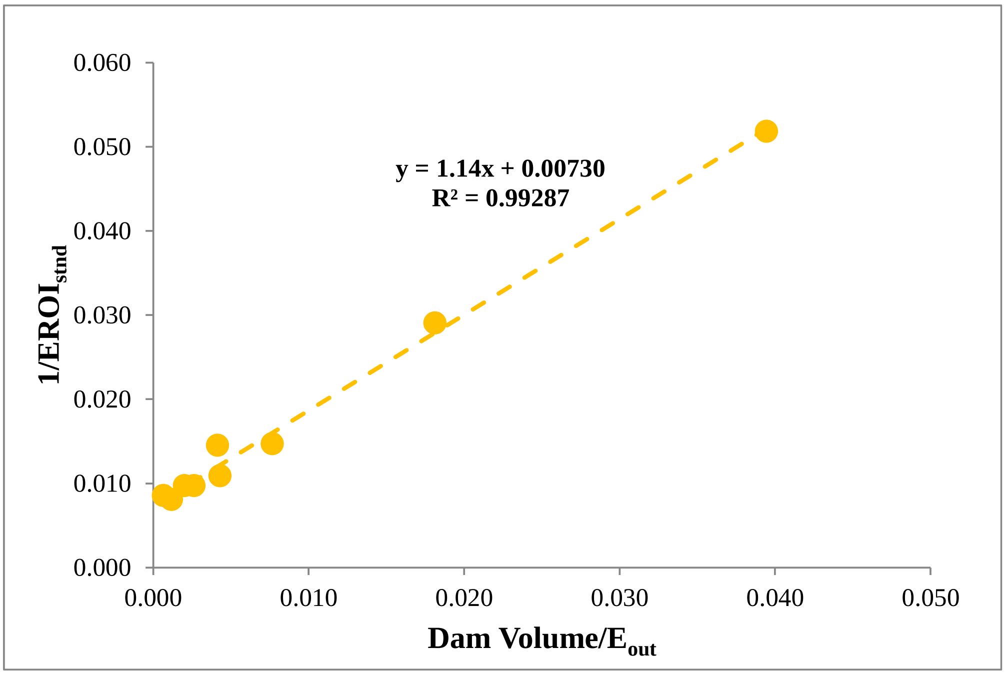


Figure 6.5 Relationship between 1/EROI$_{stnd}$ Values and Dam Volume/Energy Output for Roller Compacted Concrete Dams.

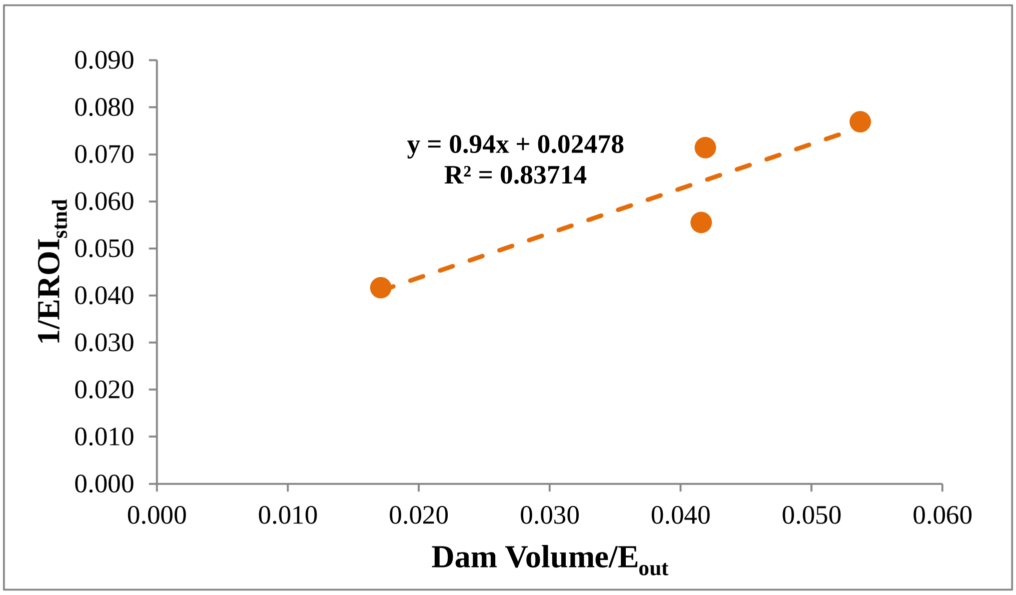


Figure 6.6: Relationship between 1/EROIstnd Values and Dam Volume/Energy Output for Zone Type Earth-Fill Dams.

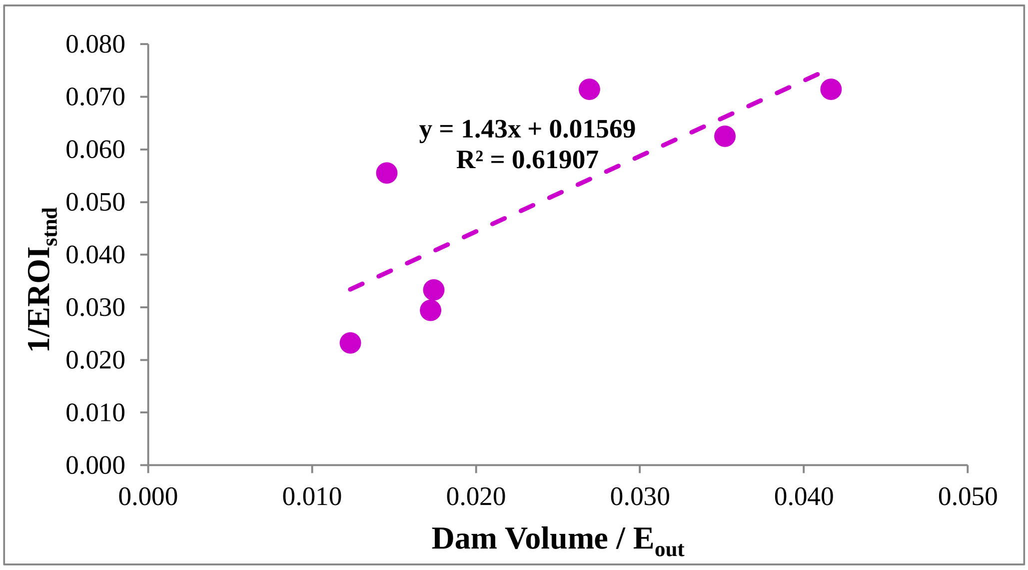


Figure 6.7 Relationship between 1/$EROI_{stnd}$ Values and Dam Volume/Energy Output for Zone Type Rock-Fill Dams.

For most of the dam types, a linear regression between 1/$EROI_{stnd}$ and Dam Volume/E_{out} shows a strong relationship, which indicates Dam Volume/E_{out} can be used to predict $EROI_{stnd}$ with some accuracy.

There are two exceptions. At present there is a lack of Composite Dams and therefore a lack of data to correlate. For Zone Type Rock-Fill Dams, the correlation coefficient shows a moderately positive correlation. There are two possible outliers, the data points (0.0269, 0.0714) and (0.0146, 0.0556), which represents Tha Htay (111 MW) and Upper Kengtaung (51 MW). These two sites fall outside the overall pattern of the scatter plot due to the fact that these two power plants have the large amount of energy embedded in the spillways and a lower amount of energy at the ground work stages.

Using the linear equations in Figures 6.1 to 6.7, coefficients a and b may be determined for each dam type.

For Concrete Faced Rock-Fill Dam,

$$\frac{1}{\mathrm{EROI_{stnd}}} = 0.00817 + 1.82\ (\frac{\mathrm{Dam\ Volume}}{\mathrm{E_{out}}}) \quad (6\text{-}5)$$

For Gravity Dam,

$$\frac{1}{\mathrm{EROI_{stnd}}} = 0.01156 + 0.81\ (\frac{\mathrm{Dam\ Volume}}{\mathrm{E_{out}}}) \quad (6\text{-}6)$$

For Homogeneous Earth-Fill Dam,

$$\frac{1}{\mathrm{EROI_{stnd}}} = 0.01765 + 1.15\ (\frac{\mathrm{Dam\ Volume}}{\mathrm{E_{out}}}) \quad (6\text{-}7)$$

For Roller Compacted Concrete Dam,

$$\frac{1}{\mathrm{EROI_{stnd}}} = 0.00730 + 1.14(\frac{\mathrm{Dam\ Volume}}{\mathrm{E_{out}}}) \quad (6\text{-}8)$$

For Zone Type Earth-Fill Dam,

$$\frac{1}{\mathrm{EROI_{stnd}}} = 0.02478 + 0.94\ (\frac{\mathrm{Dam\ Volume}}{\mathrm{E_{out}}}) \quad (6\text{-}9)$$

For Zone Type Rock-Fill Dam,

$$\frac{1}{\mathrm{EROI_{stnd}}} = 0.01569 + 1.43\ (\frac{\mathrm{Dam\ Volume}}{\mathrm{E_{out}}}) \quad (6\text{-}10)$$

Based on Equations (6-5) to (6-10), the $\mathrm{EROI_{stnd}}$ values for each different dam types can be predicted. For instance, if one wants to construct a Concrete Faced Rock-Fill Dam corresponding with a specific energy generation, the needed amount of energy invested in “Dam Volume” can be roughly estimated by using the predictive equations designed by Kansai Electric Power Co., Inc., as described in Chapter 5 (Mizuta & Takeda, 2015). After that, the $\mathrm{EROI_{stnd}}$ value can be predicted from the Equation (6.7).

6.3 Estimation of EROI and Energy Expended for Future Electricity Supply in Myanmar

It has been stated in Chapter 4 that the electricity generation target of Myanmar in 2030 is estimated as 136605 GWh (Installed Capacity - 28 GW) to fulfil the electricity requirement for future projected population, moderate economic growth (Ministry of Electric Power, 2015) and regional energy trade purposes (Kattelus et al., 2015). This generation mix target comes from hydropower, 83444 GWh (61%), natural gas 32780 GWh (24%), coal 14420 GWh (11%) and renewables (such as solar, wind and biomass), 5961 GWh (4%) based on CEPA analysis.

In this section, the planned hydropower plants to fulfil future generation, 83444 GWh in year 2030, are proposed and the energy expended analysis is also carried out. In addition, a new generation mix scenario is analysed based on the calculated $EROI_{stnd}$ results coupled with the energy expended analysis for year 2013, 2020 and 2030.

Electricity generation sources in 2013, 2020 and 2030 are described in Table 6.1. The total electricity generation data are in regard to "National Electricity Master Plan" (2014-2030) designed by JICA et al., there might be some differences between actual and plan generation for year 2013 (Ministry of Electric Power, 2015 & Japan International Cooperation Agency et al., 2014).

Table 6.1 Electricity generation types in 2013, 2020 and 2030 (Japan International Cooperation Agency et al., 2014).

Generation Type	Unit	Year 2013	Year 2020	Year 2030
Hydropower	GWh	9901	14657	83444
Coal	GWh	-	16936	14420
Natural Gas	GWh	4701	16331	32780
Renewables	GWh	736	596	5961
Total	**GWh**	**15338**	**48520**	**136605**

As the energy expended analysis for electricity generation from hydropower resources is based on the $EROI_{stnd}$ values calculated from this study, the generation breakdown for hydropower resources is needed to be clarified. The total generation in Table 6.1 is mixed with the generation from small hydropower plants, run-of river hydropower plants and storage type hydropower plants. As the $EROI_{stnd}$ values are only for the storage type hydropower plants, the needed EROI values for small, run-of river and some storage type hydropower plants are estimated as the average electrical EROI (GWh/GWh-e) value of small hydropower plant, 22 to facilitate the analysis (Walmsley et al., 2014).

For year 2013, the $EROI_{stnd}$ values calculated for the constructed storage type hydropower plants commissioning before and at the year 2013, a total generation amount 6977 GWh are used. For the rest of generation amount 2924 GWh (out of a total 9901 GWh) come from run-of river power plants and small hydropower plants (installed capacity less than 10 MW) those commissioning before and at the year 2013, the estimated average electrical EROI (GWh/GWh-e) value of small hydropower plant, 22, is used (Walmsley et al., 2014).

For total generation 14657 GWh in 2020, the $EROI_{stnd}$ values for the constructed storage type hydropower plants commissioning before and at 2015, 8306 GWh are used. According to data from MOEP, three under-construction power plants are estimated to be commissioned before year 2020, the $EROI_{stnd}$ values for those plants' generation, 1153 GWh are included. The annual generation from run-of river power plants 3232 GWh and small power plants (installed capacity less than 10 MW) 150 GWh before commissioned year 2020 and others 1816 GWh, (that may be either storage or run-of river or small power plants) for those generation, the estimated average electrical EROI (GWh/GWh-e) value of small hydropower plant, 22, is used (Walmsley et al., 2014).

For year 2030, the $EROI_{stnd}$ values of the constructed storage type plants before and at the year 2015, 8307 GWh and for five under-construction stage storage type power plants those are estimated to be commissioned before year 2030, 5962 GWh are included. The annual generation from run – of river power plants 3232 GWh and small power plants (installed capacity less than 10 MW) 150 GWh before commissioned year 2020 and others 3627 GWh, (that may be either storage or run-of river or small power plants) for those generation, the estimated average electrical EROI (GWh/GWh-e) value of small hydropower plant, 22, is used (Walmsley et al., 2014).

As the needed hydropower generation in 2030 is 83444 GWh, where the above – mentioned generation is only 21278 GWh, therefore the numbers of planned power plants (for additional requirement of annual generation, 62166 GWh) are needed to be proposed.

As presented in Table 6.2, the total energy generation for the calculated $EROI_{stnd}$ values for planned power plants are 162252 GWh coupled with their Energy Payback Time (EPT). Hence, the planned power plants by year 2030 will be selected and proposed to fulfil the required 62166 GWh.

Table 6.2 Estimated $EROI_{stnd}$ values for planned hydropower plants.

No.	Projects	$EROI_{stnd}$	Energy Payback Time	Installed Capacity (MW)	GWh/y	Level
1	Xo Luu	35	3rd year	160	775	Planned
2	Manipour	43	2nd year	380	1903	Planned
3	Maing Wah	54	2nd year	60	274	Planned
4	Mantaung	55	2nd year	225	992	Planned
5	Wun Tar Pin	62	1st year	33	170	Planned
6	Kengtong	75	1st year	128	655	Planned
7	Keng Yang	77	1st year	40	204	Planned
8	Shweli 2	85	1st year	520	2814	Planned
9	Gawlan	91	1st year	120	594	Planned
10	Chi Phwae	92	1st year	3400	17770	Planned
11	Tongxinqiao	93	1st year	340	1695	Planned
12	Khankan	93	1st year	140	642	Planned
13	Dapein 2	97	1st year	140	769	Planned
14	Yee Nan	97	1st year	1200	6182	Planned
15	Longdin	98	1st year	570	2800	Planned
16	Hutgyi	103	1st year	1360	7325	Planned
17	Maingtong	103	1st year	7000	34717	Planned
18	Khaunglanphuu	110	1st year	2700	14730	Planned
19	Wusauk	117	1st year	1800	10140	Planned
20	Laizar	117	1st year	1900	10440	Planned
21	Naung Pha	117	1st year	1200	6650	Planned
22	Ywathit	124	1st year	4000	21789	Planned
23	Phizaw	124	1st year	2000	11080	Planned
24	Kunlong	127	1st year	1400	7142	Planned
	Total				**162252**	

6.3.1 Planned Storage Type Hydropower Plants Proposal

As one of the best sustainable and renewable energy resources, hydropower has tremendous benefits such as the generation technology is clean. However, there are also some adverse effects on the construction of the hydropower plants especially large scale hydropower plants, in which the major concern is the environmental and social impacts. Both impacts must be identified before the power plants construction and the detailed impact assessment must be carried out to mitigate any unnecessary problems.

Although large scale hydropower plants have unique characteristics, they may include

(1) Huge infrastructure because of its physical structure

(2) Most projects are located in rural areas, thus the impacts affect the vulnerable communities and endangered species at the proposed sites

(3) Hydropower electricity benefits are mostly enjoyed by the urban population rather than rural population, thus the rural people want to protect the "exploitation" (Kaunda et al., 2012).

Furthermore, large scale power plants are known to emit a small amount of Greenhouse Gases (GHG), especially methane (CH_4) and carbon dioxide (CO_2) as the buried organic matter decomposition in the reservoir due to the insufficiency of oxygen. However, compared to other electricity generation resources, the levels of GHG emissions are very low in hydropower generation technology (Kaunda et al., 2012). Therefore, the emissions factor for hydropower resources in the CEPA analysis has been done in Chapter 4 is estimated as near 0 kt CO_2-e/GWh (Walmsley et al., 2014).

The outlook for the series adverse effect of the possibility of small, medium and large scale power plants in this Master Plan are analysed as illustrated in Table 6.3. A large scale hydropower plant is defined as an installed capacity above 1000 MW in that case (Japan International Cooperation Agency et al., 2014).

Table 6.3 Outlook of Series adverse impacts for hydropower resources (Japan International Cooperation Agency et al., 2014).

Potential Serious Adverse Impact	Large Scale Hydropower	Small / Medium Scale Hydropower
Resettlement / Indigenous People	**Likely** **large scale**	Possible
Ecosystem / Rare Species	**Likely** **large scale**	Possible
Water Pollution / Water Usage	Likely water quality degradation by reservoir	Reduction of run-of in some river section
Air Pollution	None	None
Greenhouse Gas Emission	None, if timber remain in reservoir, CH_4 likely	None
{Ref.} Suitable Load	Peak Load Middle Load	Middle Load Base Load

The installed capacities of 11 out of 24 planned power plants as shown in Table 6.2 are above 1000 MW. At the same time, the $EROI_{stnd}$ values of most of them are high, ~100. In the case of the additional electricity generation requirement for hydropower in 2030, policy makers need consider a trade-off between the benefits of the best EROI and the possibilities of risks and impacts for large scale hydropower plants construction, especially on the environmental and social impacts point of view.

Regarding the environmental impact issues of hydropower plants in Myanmar, the complete project proposals for the planned power plants need to be submitted in terms of either the Preliminary Environmental Impact Assessment (PEIA) or full Environmental Impact Assessment (EIA). Any project less than the installed capacity of 15 MW or with a reservoir storage capacity of less than 200 Mm^3 or with a reservoir area of less than 1500 ha requires a PEIA, whereas any larger projects require full a EIA (Doran et al., 2014). Therefore, when the proposed planned power plants are selected, the energy policy makers carefully consider based on these Environmental Impact Assessment (EIA) results. Additionally, they can also use the analysis results of this study to balance the pros and cons of large scale hydropower plants on the results of the Energy Return on Investment, $EROI_{stnd}$ values and Energy Payback Time (EPT).

The planned power plants described in Table 6.4 are proposed to fulfil the estimated 61962 GWh for 2030 electricity generation target due to the following reasons:

(1) Based on the adverse impacts for large scale hydropower resources as shown in Table 6.3, the huge capacity power plants are more likely to have serious adverse effect on the environment such as water pollution, GHG emissions, ecosystem problems and resettlement problems for the indigenous people who live in the specific locations. Therefore, very large scale power plants those have the installed capacity above 3000 MW such as Maingtong (7000 MW), Ywathit (4000 MW) and Chi Phwae (3400 MW) power plants are not proposed for future generation purposes although they have very high $EROI_{stnd}$. The installed capacities of the selected power plants in Table 6.4 are between 33 MW and 1900 MW, and those capacities are reasonable capacity for Myanmar not only from the environmental point of view but also the social and political point of view.

(2) The proposed plants are also selected based on their suitable location of tributaries, creeks, rivers and main streams. Manipour (380 MW) power plant on Manipour River is the only plant as Chindwin River hydropower scheme to develop this region. Shweli 2 (520 MW) power plant is selected as one of a series of cascade projects, the constructed run-of river power plant, Shweli 1 (600 MW) and the under-construction storage type power plant, Shweli 3 (1050 MW) on Shweli river. Dapein 2 (140 MW) is also selected one of a series of cascade projects, the constructed run-of project Dapein 1 (240 MW) on Dapein River. Moreover, the storage type cascade power plants Gawlan (120 MW), Khankan (140 MW), Tongxinqiao (340 MW) and Longdin (570 MW) power plants on Naw Chan Kha River, another cascade storage type power plants Keng Tong (128 MW), Wun Tar Pin (33 MW), Xo Luu (160 MW), Maing Wah (60 MW) and Keng Yang (40 MW) on Nam Lwae River, another cascade storage type power plants Yee Nan (1200 MW) and Wusauk (1800 MW) on Maykha River, a single storage type power plant Laizar (1900 MW) on Malika River, cascade storage type power plants, Kunlong (1400 MW), Naung Pha (1200 MW), Man Taung (225 MW) and Hutgyi (1360 MW)

on Thanlwin River are proposed as the newly tributaries and main streams projects.

(3) In terms of EROI outlook, the selected power plants have very high $EROI_{stnd}$ values from 35 to 127. By means of EPT, most of the selected power plants have high energy payback time even the first year after the plants being commissioned except 4 power plants as shown in Table 6.4. Although the EPT of Xo Luu (160 MW), Manipour (38 MW), Maing Wah (60 MW) and Man Taung (225 MW) power plants are longer than the first year, their payback time is either second year or third year, therefore quick energy return can return back to the society.

With clarification of $EROI_{stnd}$ values for the energy expended analysis for electricity generation from hydropower resources, the EROI values for other resources such as coal, natural gas and renewables (solar, wind and biomass) are needed. On this account, the EROI values for coal and natural gas values are estimated as the average electrical EROI values (GWh/GWh-e) of 25 and 13 (Walmsley et al., 2014). While the generation of renewables in 2030 is targeted from solar, wind and biomass, the average electrical EROI (GWh/GWh-e) values for solar PV is only used to facilitate this study and estimated as 6 (Walmsley et al., 2014).

Table 6.4 Proposed $EROI_{stnd}$ values coupled with planned projects generation in 2030.

No.	Projects	$EROI_{stnd}$	EPT	Installed Capacity (MW)	GWh/y	Level
1	Xo Luu	35	3rd year	160	775	Planned
2	Manipour	43	2nd year	380	1903	Planned
3	Maing Wah	54	2nd year	60	274	Planned
4	Mantaung	55	2nd year	225	992	Planned
5	Wun Tar Pin	62	1st year	33	170	Planned
6	Kengtong	75	1st year	128	655	Planned
7	Shweli 2	85	1st year	520	2814	Planned
8	Keng Yang	77	1st year	40	204	Planned
9	Gawlan	91	1st year	120	594	Planned
10	Tongxinqiao	93	1st year	340	1695	Planned
11	Khankan	93	1st year	140	642	Planned
12	Dapein 2	97	1st year	140	769	Planned
13	Yee Nan	97	1st year	1200	6182	Planned
14	Longdin	98	1st year	570	2800	Planned
15	Hutgyi	103	1st year	1360	7325	Planned
16	Wusauk	117	1st year	1800	10140	Planned
17	Laizar	117	1st year	1900	10440	Planned
18	Naung Pha	117	1st year	1200	6650	Planned
19	Kunlong	127	1st year	1400	7142	Planned
	Total				**62166**	

6.3.2 Energy Return on Energy Invested Analysis

The estimated energy expended in 2013, 2020 and 2030 against the electricity generation in Myanmar for different resources is illustrated in Figure 6.8, 6.9 and 6.10. The energy expended is estimated using the calculated $EROI_{stnd}$ values from this analysis for storage type hydropower resources, the estimated average EROI (GWh/GWh-e) values for hydropower (i.e. for small, run-of river and some storage type hydropower plants those data are not available for EROI calculation and represented as hydropower-others), for coal, natural gas and solar PV are estimated as 22, 25, 15 and 6 respectively (Walmsley et al., 2014). Although the renewables energy targeted in 2030 comes from solar, wind and biomass, solar PV of EROI values (GWh/GWh-e) is used in this study.

Hence, total electricity generation for year 2013 is 15338 GWh, which come from hydropower 9901 GWh, coal 736 GWh and natural gas 4701 GWh. For year 2020, hydropower 14657 GWh, coal 16936 GWh, natural gas 16331 GWh and renewables (solar PV) 596 GWh are accounted for the total electricity generation, 48520 GWh. For year 2030, total electricity generation is 136605 GWh, in which hydropower account for 83444 GWh, coal account for 14420 GWh, natural gas account for 32780 GWh and solar PV account for 5961GWh (Ministry of Electric

Power, 2015). The energy expended (GWh-e) values in those figures are calculated by multiplying the energy generation (GWh) with the inverse of $EROI_{stnd}$ values and average EROI (GWh/GWh-e) values.

Figure 6.8 and 6.9 depict the energy expended situation in 2013 and 2020, in which hydropower gives the significant better energy return rather than coal fuel and natural gas based on the resulted $EROI_{stnd}$ values analysis in this study. However, in terms of the overall EROI values, hydropower offer a slightly better result other than coal, natural gas and solar in both years, 26 in 2013 and 25 in 2020.

The composite curves comparison for the electricity generation (GWh) and energy expended (GWh-e) for year 2013, 2020 and 2030 are presented in Figure 6.10. Due to the significant increased electricity demand from 2013 to 2020, from 15338 GWh to 48520 GWh with the growth of 68%, energy expended has been increased by 70 %, from 784 GWh-e to 2634 GWh-e. Similarly, energy expended has been increased 52 % from 2020 to 2030, from 2634 GWh-e to 5524 GWh-e due to the fact that the electricity growth demand within this decade is 64%, from 48520 GWh in 2020 to 136605 GWh in 2030.

As illustrated in Figure 6.8, 6.9 and 6.10, the calculated $EROI_{stnd}$ values from the analysis of this study and the average overall EROI values are plotted as the EROI values for hydropower. Both of them offer the best energy return for energy invested other than coal, natural gas and solar PV in year 2013, 2020 and 2030. On this account, the result is not surprising that the overall EROI values, 59 for hydropower gives the highest energy return in 2030 which is significantly higher than other fossil and non-fossil fuels resources due to the fact that hydropower plants generated high annual energy coupled with their high $EROI_{stnd}$ values resulted in higher overall EROI values.

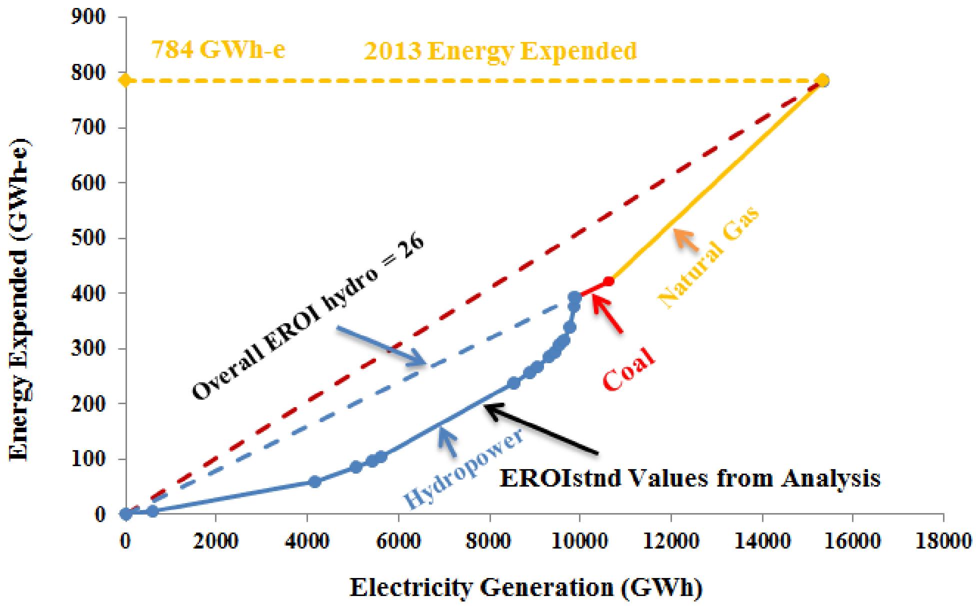


Figure 6.8 Myanmar energy expended for electricity generation in 2013. (Generation Data from Ministry of Electric Power, 2015).

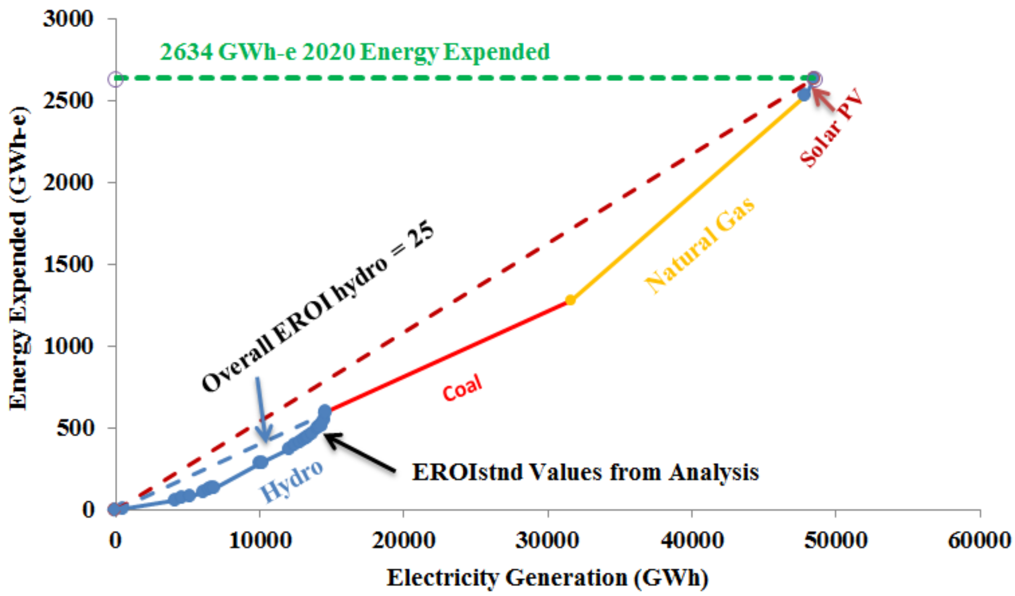


Figure 6.9 Projected energy expended for electricity generation in 2020. (Generation data from Ministry of Electric Power, 2015).

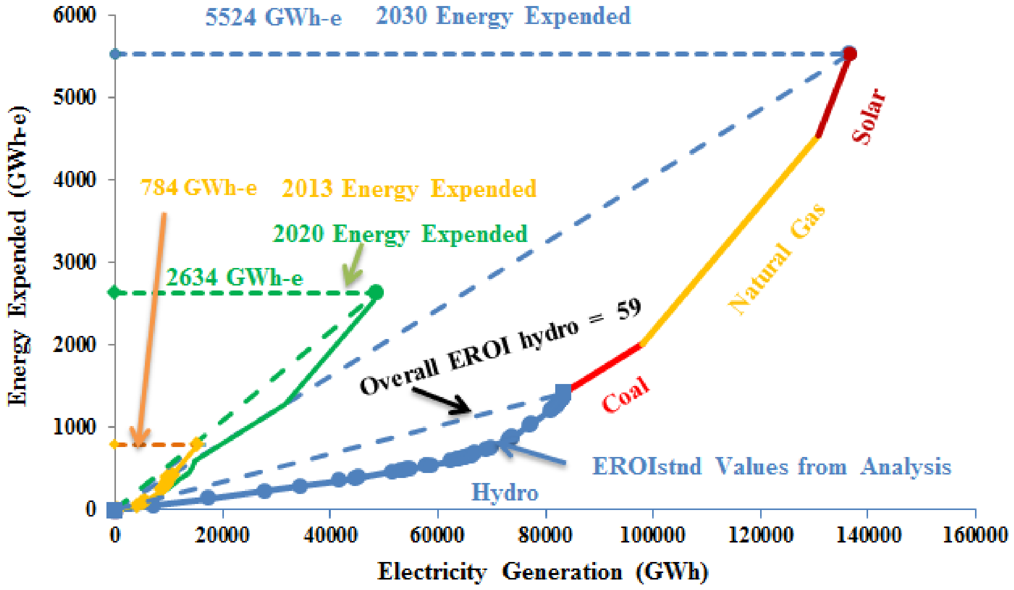


Figure 6.10 Energy expended comparison in Year 2013, 2020, 2030 for Myanmar Electricity Sector. (Generation data from Ministry of Electric Power, 2015).

Hence, coal thermal power generation and natural gas power generation technology have been used in Myanmar since long time ago as illustrated in Figure 6.11. In this figure, the majority of hydropower is included as the renewables. Other renewables such as solar, wind and biomass are targeted to generate mass generation for future purposes mainly from 2020 to 2030. Based on the EROI analysis, the result provides solar PV has very low EROI value compared with other resources in terms of its immature technology in the developing country. It is obvious that solar PV mass generation is a new renewable resource for Myanmar; therefore, EROI is much lower than other generations thus the significant government intervention is needed for widespread adoption of the economics. Although Solar PV is at the early stages of technology in Myanmar, innovative practices can be improved such as manufacturing and installation methods during 10 years (from 2020 to 2030). After that, it is expected to gain more commercial acceptance leading to the improvement of EROI values after the technology developing and mass producing.

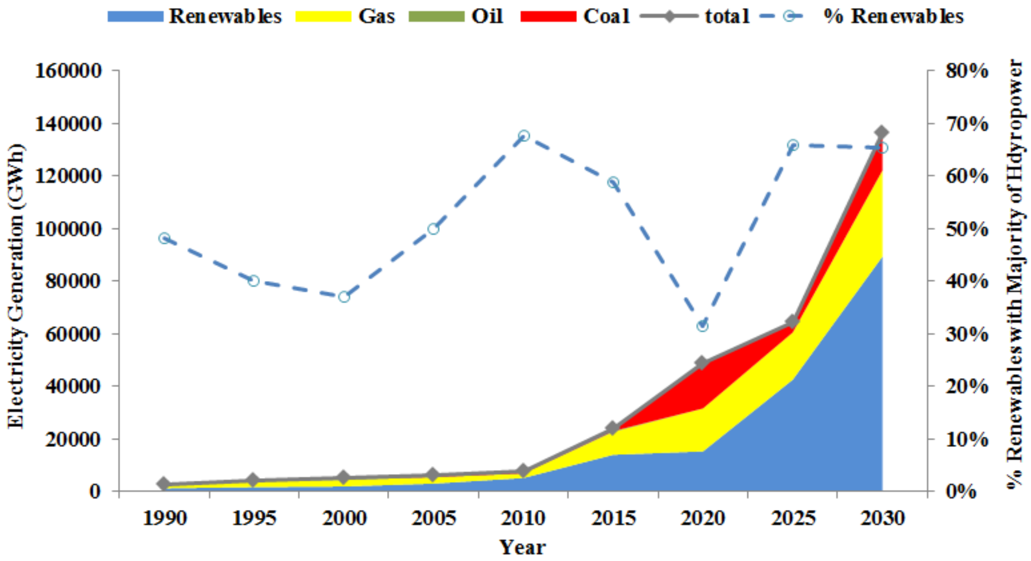


Figure 6.11 Historical and predicted electricity generations in Myanmar through to 2030. (Data from Ministry of Electric Power, 2015).

The great amount of increased in energy demand due to the inclination of electricity generation from 2013 to 2030 causes the increase in overall carbon emissions within about three decades. Based on the 19 proposed planned power plants, the energy expended in year 2030 is needed to use 5524 GWh-e with overall hydropower EROI of 59. The carbon emissions from this MOEP' selected scenario has been expressed as 24403 kt CO_2-e in Chapter 4 which is 17 % of emissions reduction from 29516 kt-CO_2-e.

6.3.3 Recommendations on Extendable Planned Storage Type Hydropower Plants in Generation Mix Target by year 2020 and 2030

It is observed that the carbon emissions in Myanmar electricity sector by year 2020 and 2030 could be obviously reduced by using a useful CEPA technique in combination with EROI analysis in generation mix options of "National Electricity Master Plan" (2014-2030) proposed by JICA et al., 2014.

For year 2020, instead of too much electricity generation from coal resources those have significant high carbon emissions, a certain amount of electricity generation is switched from coal resource, 14814 GWh to hydropower resources those have zeroing emissions, 14814 GWh at the original Master plan as shown in Table 6.5.To fulfil this target, the desired 13 planned power plants with a total generation of 14287 GWh are added in the original plan after those are selected from Table 6.2. A few amount of generation gap, 527 GWh is added to hydropower (others) in Table 6.5. The reason why only these 13 power plants are recommended is that the installed capacity of those 13 proposed plants range from 33 MW to 570 MW, those can only be finish within 4 years (from 2016 to 2020). As shown in Table 6.2, the rest of the power plants installed capacity are over 1000 MW up to 7000 MW. As the total construction year of Shweli 3 (Installed Capacity 1050 MW) nearly take 10 years according to the information from MOEP, the large power plants cannot be finished within 4 years (from 2016 to 2020) to fulfil 2020 generation target. The construction period of the constructed and under-construction power plants are expressed in their respective Appendices. Therefore, the needed generation gap, 527 GWh is added to hydropower (others) in Table 6.5. It could be the generation amount of either run-of rivers or small power plants that will be constructed within 4 years period.

Table 6.5 Comparison of plan and recommended power plants for year 2020 and 2030 generation.

Generation Type	Level	Year 2020 (Plan)	Year 2020 (Recommend)	Year 2030 (Plan)	Year 2030 (Recommend)	EROI (GWh/GWh-e)
Hydropower	Planned	-	-	7142	7142	127
Hydropower	Planned	-	-		11080	124
Hydropower	Planned	-	-	10140	10140	117
Hydropower	Planned	-	-	10440	10440	117
Hydropower	Planned	-	-	6650	6650	117
Hydropower	Planned	-	-	7325	7325	103
Hydropower	Planned	-	2800	2800	2800	98
Hydropower	Planned	-	769	769	769	97
Hydropower	Planned	-	-	6182	6182	97
Hydropower	Planned	-	1695	1695	1695	93
Hydropower	Planned	-	642	642	642	93
Hydropower	Planned	-	594	594	594	91
Hydropower	Constructed	599	599	599	599	85
Hydropower	Planned	-	2814	2814	2814	85
Hydropower	Planned	-	204	204	204	77
Hydropower	Planned	-	655	655	655	75
Hydropower	Constructed	3550	3550	3550	3550	69
Hydropower	Under-construction			1409	1409	69
Hydropower	Planned	-	170	170	170	62
Hydropower	Planned	-	992	992	992	55
Hydropower	Planned	-	274	274	274	54
Hydropower	Under-construction	500	500	500	500	49
Hydropower	Constructed	604	604	604	604	47
Hydropower	Planned		1903	1903	1903	43
Hydropower	Planned		775	775	775	35
Hydropower	Constructed	911	911	911	911	34
Hydropower	Under-construction			3400	3400	34
Hydropower	Constructed	370	370	370	370	30
Hydropower	Constructed	190	190	190	190	24
Hydropower	Constructed	152	152	152	152	23
Hydropower	Run - off river	3231.6	3231.6	3232	3232	22

Table 6.5 contd.

Generation Type	Level	Year 2020 (Plan)	Year 2020 (Recommend)	Year 2030 (Plan)	Year 2030 (Recommend)	EROI (GWh/GWh-e)
Hydropower	Small	149.78	149.78	150	150	22
Hydropower	Others	1816	2343	3627	3627	22
Hydropower	Constructed	454	454	454	454	19
Hydropower	Constructed	330	330	330	330	18
Hydropower	Under-construction	267	267	267	267	18
Hydropower	Constructed	165	165	165	165	16
Hydropower	Constructed	120	120	120	120	14
Hydropower	Constructed	262	262	262	262	14
Hydropower	Under-construction	386	386	386	386	14
Hydropower	Constructed	123	123	123	123	13
Hydropower	Constructed	120	120	120	120	10
Hydropower	Constructed	76	76	76	76	8
Hydropower	Constructed	134	134	134	134	6
Hydropower	Constructed	117	117	117	117	3
Hydropower	Constructed	30	30	30	30	2
Hydropower (Total)		**14657**	**29471**	**83444**	**94524**	
Coal		**16936**	**2122**	**14420**	**3340**	**25**
Natural Gas		**16331**	**16331**	**32780**	**32780**	**13**
Solar PV		**596**	**596**	**5961**	**5961**	**6**
Total		**48520**	**48520**	**136605**	**136605**	

For year 2030, switching from coal resource, 11080 GWh to hydropower resource, 11080 GWh, and the amount is added in year 2030 original plan as shown in Table 6.5. By proposing just one more planned power plant which has generation 11080 GWh as shown in Table 6.2, the desired target is easily reached. Hence, the rest of the planned power plants those have very high installed capacity and generation in Table 6.2 cannot be selected to switch from coal resource.

To fulfil the needed amount of generation in year 2030, the construction tasks of all the newly planned power plants should be started in 2016 because the more the power plants have large installed capacity, the more they take time to be built.

Figure 6.12 illustrates the carbon emissions reduction scenarios in year 2020 and 2030. After adding the recommended proposed power plants in the original plan, the carbon emissions in year 2020 has been significantly reduced by 62%, from 19306 kt –CO_2-e (Plan) to 7431 kt CO_2-e (Recommend) by switching coal to hydro.

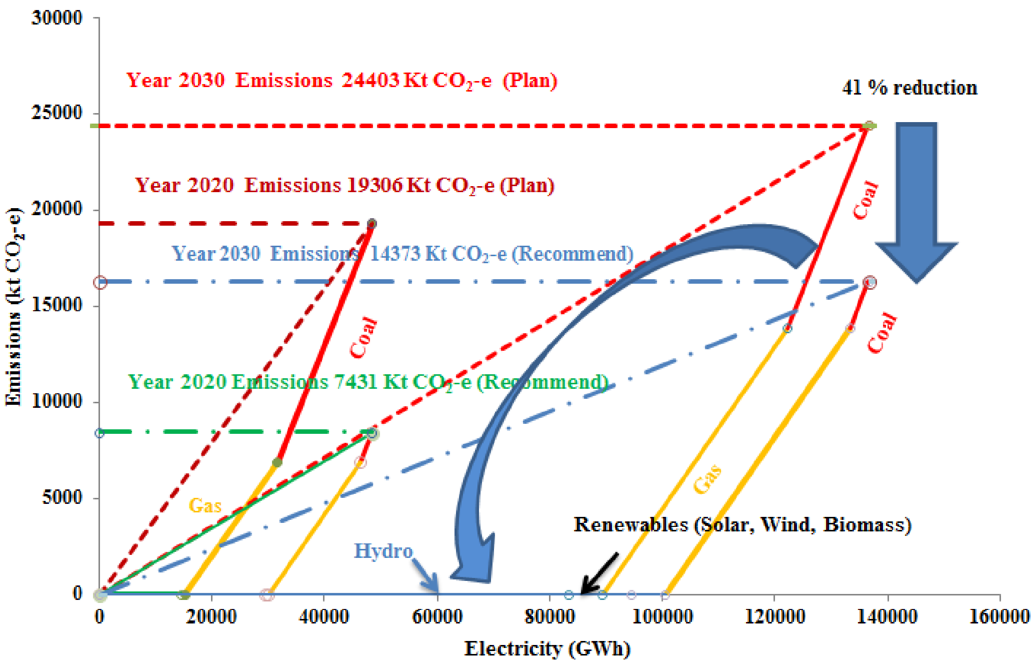


Figure 6.12 Significant emissions based on recommended option by year 2030. (Generation data from Ministry of Electric Power, 2015).

Similarly, for year 2030, a tremendous reduction in carbon emissions has been examined from 24403 kt CO_2-e (Plan) to 14373 kt CO_2-e (Recommend), almost 41 % reduction due to the recommended planned power plants added in the original plan by switching coal to hydro.

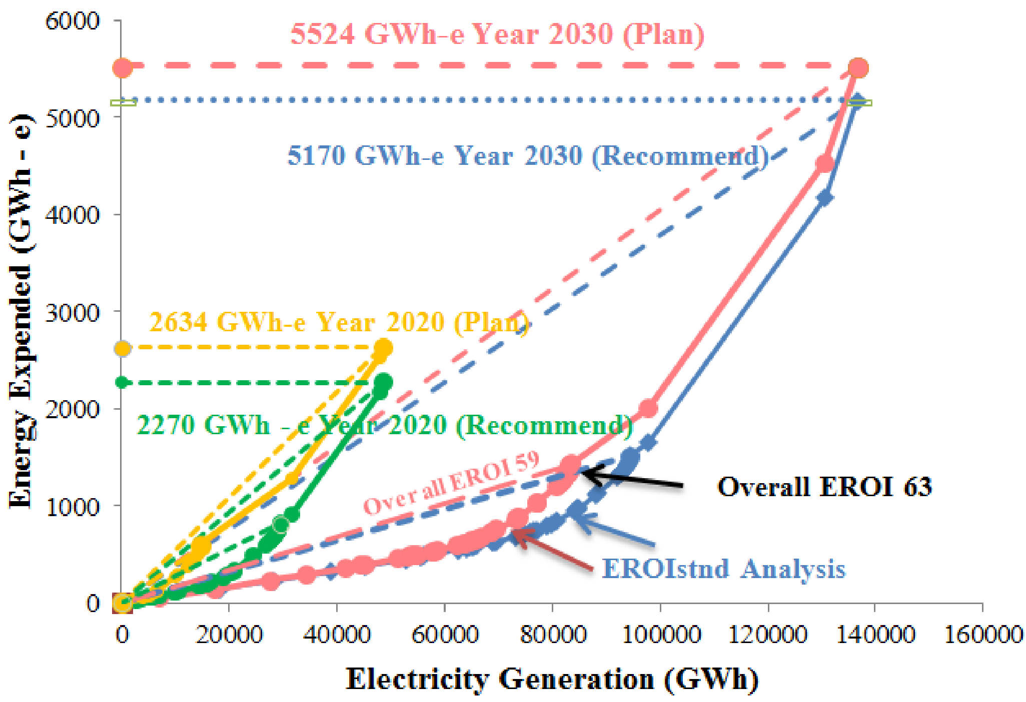


Figure 6.13 Energy expended analysis based on recommend planned hydro plants. (Generation data from Ministry of Electric Power, 2015).

Based on the recommend proposed planned power plants and generation mix target, energy expended analysis against the respective generation in year 2020 and 2030 are illustrated in Figure 6.13.

As the energy expended has been 2634 GWh-e in year 2020 with respect to the previous plan, it has been decreased to 2270 GWh-e, 14 % reduction of energy expended from 2634 GWh-e to 2270 GWh-e together with the a slight changes in overall EROI values of hydropower from 25 to 36. By year 2030, the energy expended has been declined from 5524 GWh-e to 5170 GWh-e, 6 % coupled with changes in overall EROI values of hydropower resources from 59 to 63.

Although the carbon emissions from Myanmar electricity sector can be reduced to a certain extent by year 2020 and 2030 based on the National Electricity Master plan, a more realistic approach is significantly found out by applying the combination with CEPA techniques and EROI methodology especially in hydropower sector. The results from the recommended proposed plans for the respective year of generation mix target have shown a holistic approach of strategic electricity master plan in year 2020 and 2030. Therefore, future purposes, it is recommend that most of the growth in electricity generation will need to come from renewables, hydropower and solar PV in 2030. Due to the best possible projection from this study from recommended option of hydropower, it is almost 10 times increase from 9901 GWh to 94524 GWh. In so doing, the installed capacity of hydropower need to be increased from 2.26 GW in 2013 to 21 GW in 2030. As the current installed capacity is 3.15 GW in 2015, the strategic plans for the construction of new hydropower plants are needed simultaneous with the implementation of the main power stations, sub stations, transmissions lines and distributions lines for 2030 future generation purposes.

To drive the electricity market towards hydro and solar PV focus on emissions reduction, the government needs to be carried out the efficient and effective plans in electricity sector. Formulating the best possible regulatory framework for electricity generation mix by using minimum non-renewable energy expenses to meet the electricity demand and focus on particular emissions reduction, planning on renewable energy technology development such as grid connected Solar PV power plant, the research programme on other renewable options like wind and geothermal are the priority implementation measures. Moreover, continual implementation in carbon emissions reduction activities such as Land Use Land Use Change and Forestry – LULUCF activities under the Clean Development Mechanism-CDM of United Nations Framework Convention on Climate Change (UNFCCC) (United Nations Framework Convention on Climate Change, 2014), Reducing Emissions from Deforestation and Forest Degradation REDD+ activities and Energy Efficiency & Conservation measures, more investing in a new renewable energy technology like tidal and wave energy and setting reasonable tariff structure for both generators and users are also a series of measures to improve the sustainable Myanmar electricity sector.

6.4 Conclusions

This chapter discusses the correlation analysis between $EROI_{stnd}$ values and the ratio of energy costs and energy production of different dam types which can provide the insights for better understanding of relationship between those two variables. Moreover, the linear model regression equations formulated from the resulted $EROI_{stnd}$ values of 47 storage type hydropower plants also assist the prediction of $EROI_{stnd}$ values for future hydropower plants' construction based on different dam types. Based on the energy expended analysis on different years' energy generation, the $EROI_{stnd}$ values resulted from this study generally revealed that hydropower can significantly provide the best energy return on energy investment other than fossil fuels and other immature renewable energy resource.

Furthermore, based on the energy generation mix target in 2030, Myanmar can achieve the reasonable goal of emissions reduction with the focus clearly on tenfold expansion of hydro from 2013 levels and an increase in solar PV capacity over the same period. The 69% renewable target from hydropower will bring Myanmar to the lower carbon emissions level to a certain extent. The formulation of supportive energy policies, implementation of much renewables, hydro and solar in the energy mix for lowering CO_2 emission to the atmosphere are to be carried out to accomplish as the country's goal.

Chapter 7
Conclusions and Recommendations for Future Work

7.1 Conclusions

The best possible future electricity generation mix for Myanmar has been identified by using a combination of EROI and CEPA analysis techniques. The best mix fulfils the initial goal of Ministry of Electric Power, Myanmar which is to generate total electricity, 136605 GWh from renewable and non-renewables resources by year 2030, while maintaining annual electricity generation growth rate 13%, while achieving the least amount of carbon emissions. To meet with this target, total generation should come from hydropower 94524 GWh (69%), natural gas 32780 GWh (24%), coal 3340 GWh (2.5%) and other renewables such as solar, wind and biomass, 5961 GWh (4.5 %). The carbon emissions target is 14373 kt-CO_2-e. To meet this best case 20 planned power plants are required and the anticipated extra energy expended for the new capacity is 5170 GWh-e resulting in overall EROI of hydropower, 63.

MOEP previously selected a suitable option proposed by JICA et al., based on the "National Electricity Master Plan" (2014-2030). If this option is followed the generation mix will include much more fossil fuel plants with hydropower reduced to 83444 GWh (61%), coal increased to 14420 GWh (11%), natural gas the same at 32780 GWh (24%) and other renewables the same at 5961 GWh (4%). The carbon emissions will stand at 24403 kt-CO_2-e for this scenario.

To meet a hydropower resource generation of 83444 GWh, 19 planned hydro power plants are required. The new capacities have high $EROI_{stnd}$ values, high Energy Payback Time (EPT) and in terms of the energy expended an extra 5524 GWh-e is needed resulting in overall EROI of hydropower, 59.

Since the aim of this study is to promote a vital role of hydropower in electricity sector, it is therefore recommended that scenario one of 69% hydro be selected for Myanmar by 2030. It is evident that the high hydro generation mix would bring the lowest carbon emissions results in electricity sector by year 2030 without significant penalty to energy expended. Specifically Myanmar can achieve its electricity generation target of 136605 GWh by year 2030, while maintaining its annual energy generation growth rate of 13%, while reducing carbon emissions amount by 10 Mt CO_2-e, approximately 41%, (from 24403 kt CO_2-e to 14373 kt CO_2-e), while using less energy expended in electricity sector 5170 GWh-e (decrease 354 GWh-e from 5524 GWh-e of the previous option) with the increased in overall EROI of hydropower from 59 to 63.

In addition to 20 planned power plants, the $EROI_{stnd}$ values of 18 existing, 5 under-construction and another 4 planned power plants, a total of 47 power plants have been analysed. Based on the resulted $EROI_{stnd}$ values, the energy policy makers now have clearer insights of the energy return on investment values of all Myanmar hydro stations, existing and future. EROI values range from 2 to 127. In general EROI values were highest for the large power plants producers.

EPT results also showed that power plants with high $EROI_{stnd}$ values have shortest energy payback time, and it is sensible to therefore construct the high $EROI_{stnd}$ plants first. Furthermore, the prediction on energy expended for specific types of hydropower plants can also be made based using the liner regression models formulated from the $EROI_{stnd}$ results of the 47 storage type hydropower plants.

7.2 Recommendations for Future Work

The following areas are recommended for further research:

(1) As $EROI_{stnd}$ calculations have only been done for storage type hydropower plants, further $EROI_{stnd}$ calculation for run-of-river plants and small hydropower plants (installed capacity < 10 MW) could be carried out to complete the picture of $EROI_{stnd}$ analysis in Myanmar electricity sector.

(2) The system boundaries on Energy Return on Investment $EROI_{stnd}$ analysis of hydropower resources could be extended up to the power systems such as electric power transmission and distribution, up to the “point of use” which consists of the energy used in extraction, refining and transportation of fuel for instance, gas station (Murphy et al., 2011). The extension of appropriate system boundaries could provide a great insight of the electricity industry of Myanmar and also the results can probably be compared with the performance of $EROI_{stnd}$ values from other countries if the same methodology and boundaries are followed.

(3) $EROI_{stnd}$ values could be calculated by using the "Price-Based Adjustment" method instead of using "Exergy-Based Adjustment" applied in this study. Therefore, the shortcomings of the current methods such as economic data, capital and labour can be captured and effectively compared to the $EROI_{stnd}$ results from both methods.

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APPENDIX 1 - SAMPLE CALCULATION

Kunn Chaung Multipurpose hydropower plant is explained as a sample for $EROI_{stnd}$ and EPT calculation.

Kunn Chaung Multipurpose Hydropower Plant

$EROI_{stnd}$ Calculation

1. **Project Description**

   The first part describes the project general information concerned with the project name, location, and type of the power plant, project status and operators. After that, the main dam and spillways information, reservoir, power station and other appurtenant structures such as headrace tunnel, surge tank, penstock, powerhouse and spillway specification etc. are described.

Table A.1 Project general information table for Kunn Chaung multipurpose hydropower plant (Ministry of Electric Power, 2015).

Project General Information		
Country		Myanmar
Location		Bago Region, 18° 29' N, 96° 26' E
Project name		Kunchaung
Type of hydropower plant		Impoundment/Storage
Status		Constructed
Purpose		Flood Control, Irrigation and Power
Irrigation area	ha	44515.42
Construction began		2002
Opening date		2012
Construction cost (million)	US$	-
Operator (s)		MOEP
Dam and Spillways		
Type of dam		Embankment, Zone Type Earth-fill
Impounds		Kun Creek
Dam height	m	73
Dam crest length	m	384
Dam volume	m^3	2211545.72
Spillway type		Service, Ogee crest and chute with flip bucket
Spillway capacity	m^3/s	127.43
Reservoir		
Gross storage capacity	Mm^3	1467.84
Active storage capacity	Mm^3	1027.49

Inactive storage capacity	Mm^3	440.35
Surface area	Km^2	-
Full reservoir level	m	161.54
Minimum drawdown level	m	146.30
Annual rainfall	mm	2540
Average annual runoff	Mm^3	941.15
Average annual discharge	m^3/s	-
Catchment area	Km^2	875.42
Power Station		
Commission date		2012
Hydraulic head	m	105.76
Configuration		3 × 20 - Vertical Francis
Installed capacity	MW	60
Annual generation	GWh/y	190
Headrace tunnel	No.	1
Length	m	2282.34
Diameter	m	5.48
Surge tank	No.	1
Height	m	54.25
Width	m	16
Penstock	No.	1
Length	m	394.72
Diameter	m	4.57
Powerhouse	No.	1
Length	m	52.73
Width	m	32.76
Height	m	28.95
Spillway	No.	Unknown
Width of spillway	m	18.28
Height of spillway	m	Unknown
Width of gate	m	Unknown
Height of gate	m	Unknown

2. Parts Calculation

Total Process Electrical Output value is calculated from the actual energy generation (GWh/y) of the plant within the plant 100- year life time in terms of heat equivalent unit (MJ) resulting in 6.84E+10 MJ.

Total Process Electrical Output

Table A.2 Total process electrical output calculation (Ministry of Electric Power, 2015).

Energy Output (Detailed Calculation)		
Power output	MW	60
Units of turbines – 3	MW	20
Combined efficiency of turbines and generators	%	0.88
Water density	kg/m^3	1000
Free fall acceleration	m/s^2	9.80
Power discharge	m^3/s	66.00
Actual power	MW	21.67
Actual annual energy	GWh/y	190
Capacity factor	-	0.36
Effective head	M	105.76
Lifetime	year	100
Actual annual energy	GWh/y	190
Total Process Electrical Output	**MJ**	**6.84E+10**

3. Total Process Energy Input Calculation

As total process energy input calculation, the eight parts are included as those being: (1) Power usage at site (2) Maintenance (3) Transportation (4) Groundwork phase (5) Preparation Stage (6) Construction stage (7) Hydraulic Equipment, and (8) Electro Mechanical Equipment.

1. Power usage at site (Operation)

As stated before, the own usage of the plant is to be approximated 0.5% of its annual energy generation, resulted in the amount of 3.42 E+8 MJ for the 100-year of the operation of the power plant

2. Maintenance

The reinvestment energy for the spillway gates, intake gates, intake screens, penstock (conduit), turbines and generators are calculated. On this account, to calculate the reinvestment energy for those elements within their technical lifetime, their respective embedded energy is needed to figure out, thus the reader is suggested to refer No.8, the calculation of the energy used in the hydraulic equipment and No.9, the calculation of the energy used in the electro-mechanical equipment. Those stages are calculated their embedded energy in terms of MJ first. After that, the reinvestment energy is considered. For the spillway gate, penstock (conduit), turbines and generators, their technical life expectancy is considered to be 60 years. Therefore, the annual reinvestment energy is accounted for 1.6% of the original appliances' embodied energy. For the lifetime of intake gate and intake screen, they are estimated to be 50 years and 35 years. Therefore, the annual reinvestment energy is accounted for 2 % and 2.8 % of their embodied energy respectively. Thus, the reinvestment embodied energy for those elements within 100-year life time is amounted for 2.25E+8 MJ.

Table A.3 Reinvestment energy at the maintenance stage.

Maintenance	**Energy (MJ)**
a. Spillway gate (stainless steel 100%, life time 60 years)	1.10E+08
b. Intake gate (stainless steel 100 %, life time 50 years)	9.41E+06
c. Intake screen (stainless steel 100%, life time 35 years)	7.32E+06
d. Penstock (conduit) (High tensile steel 100%, life time 60 years)	3.49E+07
e. Turbines (stainless steel 28%, structural steel 72%, life time 60 years)	2.00E+07
f. Generators (copper 6%, structural steel 45%, steel sheet 49% life time 60 years)	4.36E+07
Total	**2.25E+08**

3. Transportation

The mixture of natural soil and rock are excavated before any construction works are being started. Materials such as soil 30%, sand 20% and rock 30% are used to build a massive Zone Type Earth-fill Dam with a total dam volume of 2211546 m^3. Reinforced Concrete (RC) is also used for other civil work construction such as spillway, intake, headrace tunnel, surge tank, power house, tailrace channel and tailrace outlet. For all those work quantities (m^3) data are gathered from MOEP for under-construction plant or calculated by using the predictive equations described in Section 5.2.3 in Chapter 5 first, and then calculated the mass (kg) by using their respective density values (kg/m^3). Those materials are estimated to be transported from 10 km distance by using trucks and the embodied energy of trucking, 2.94 MJ/t.km is used to make the energy quality correction (MJ) which is amounted in 1.47E+08 MJ. For reinforcement transportation, all the reinforcement bars are data collected or calculated in terms of mass (kg) and assumed to be transported from Maung Takar Factory, Yangon, 240 km far from dam site by using trucks (Ministry of Electric Power, 2015). Then, they are converted to energy (MJ) which is amounted to 2.41E+06 MJ. For Kunn Chaung hydropower plant, China National Heavy Machinery Cooperation imported the electronic, mechanical equipment and hydraulic steel structure from China to Myanmar. Therefore, the shipping distance between Tianjin, China to Yangon, Myanmar is estimated to be 8785.88 km and trucking distance between Yangon to plant site is 240 km. These materials mass (kg) (calculated by No. 8 and No.9) are converted to energy (MJ) by using the embodied energy of shipping (0.1129 MJ/t.km) and trucking (2.94 MJ/t.km), resulted in 3.76E+06 MJ and 1.69E+06 MJ. In total, it is resulted as 1.55 E+8 MJ.

Table A.4 Embedded Energy at the transportation stage.

Transportation	**Energy (MJ/Kg)**
a. Materials transport	1.47E+08
b. Reinforcement transport	2.41E+06
c. Hydraulic equipment transport	3.76E+06
d. Electro mechanical equipment transport	1.69E+06
Total	**1.55E+08**

4. Energy Used in The Ground Work Phase

Excavation work quantities for the following dam and its appurtenant structures, spillway, intake, headrace tunnel, surge tank, penstock, power house, tailrace channel and tailrace outlet are gathered from MOEP or calculated by using the predictive equations, their excavation volume, V_e equations respectively. After all the excavated work quantities are calculated in terms of volume (m^3), those are converted to the energy (MJ/kg) by using the density of soil and rock mixture, 1900 kg/m^3 and embodied energy of soil 0.45 MJ/kg. Totally, the embedded energy in the ground work phase is amounted in 8.24E+8 MJ.

Table A.5 Energy used at the groundwork phase.

Groundwork phase	**Energy (MJ/kg)**
a. Dam	2.40E+08
b. Spillway	3.90E+08
c. Intake	1.07E+07
d. Headrace tunnel	6.63E+07
e. Surge tank	1.48E+07
f. Penstock	8.07E+07
g. Powerhouse	1.68E+07
h. Tailrace channel	9.93E+05
i. Tailrace outlet	3.89E+06
Total	**8.24E+08**

5. Energy used in the preparation stage

At the preparation stage, it is needed to construct an access road from the closest main road to the dam site, which is far 15 km from the power plant site and converted to embodied energy MJ by using embedded energy in roading 1875000 MJ/km, resulting in 2.81E+7 MJ.

6. Energy used at the construction stage

The work quantities for the construction phase for the following dam and its appurtenant structures are gathered from MOEP or calculated by using their respective construction volume, V_c Equations (m^3) and converted them to the energy (MJ/kg) by using the density values (kg/m^3) and embodied energy (MJ/kg). As Kunn multipurpose dam type is Zone Type Earth-fill Dam, the materials percentage is estimated to be soil 30%, sand 20 % and rock 50 %. In accordance with the materials proportion, the embedded energy in dam volume is calculated, resulting in 7.81E+08 MJ. Likewise, the other structures such as the construction work quantities for spillway, intake, headrace tunnel, etc. their reinforced concrete volume (m^3) are also calculated first. Then, these values are converted to the embedded energy (MJ/kg) by using density and energy correction value for RC, 2300 kg/m^3 and 1.04 MJ/kg. Totally, the energy used at the construction stage is 1.15E+9 MJ. It is evident that due to the massive volume of dam, 2211545.72 m^3, the energy used for dam construction is the largest which is almost 68 % of the total energy used for construction, followed by spillway 17.30%, headrace tunnel about 7% because of its long length 2282 m. However, the energy used in intake, surge tank, penstock, power house, tailrace channel and tailrace outlet are just a small percentage.

Table A.6 Energy expended at the construction stage.

Construction stage	Energy (MJ/kg)	Percentage
a. Dam	7.81E+08	67.85%
b. Spillway	1.99E+08	17.30%
c. Intake	1.54E+07	1.34%
d. Headrace tunnel	7.73E+07	6.72%
e. Surge tank	1.64E+07	1.42%
f. Penstock	2.40E+07	2.09%
g. Powerhouse	3.23E+07	2.80%
h. Tailrace channel	1.85E+06	0.16%
i. Tailrace outlet	3.65E+06	0.32%
Total	**1.15E+09**	**100.00%**

7. Energy used in the hydraulic equipment

The hydraulic equipment for the hydropower plants are generally defined as spillway gate, intake gate, intake screen and penstock (conduit). The data for the weight (kg) of those structures are gathered from MOEP or collected by their respective Equations, and converted to energy (MJ). In total, the energy used for hydraulic equipment is 9.77E+07 MJ.

Table A.7 Energy used in the hydraulic equipment.

Hydraulic equipment	Energy (MJ)
Spillway gate	6.86E+07
Intake gate	4.70E+06
Intake screen	2.61E+06
Penstock (Conduit)	2.18E+07
Total	**9.77E+07**

8. Electro mechanical equipment

This stage contains of 2 main items, turbines and generators and the calculation method is already described. Kunn Chaung hydropower plant installed three 20 MW turbines, therefore the total embodied energy is amounted to 3.97E+7 MJ.

Table A.8 Energy Invested in the turbines and generators.

Electro mechanical equipment	Energy (MJ)
Turbines	1.25E+07
Generators	2.72E+07
Total	**3.97E+07**

Total Energy Expenditures

After all the above phases are calculated, the sum of all the energy expended are 2.86E+9 MJ within the $EROI_{stnd}$ boundaries, in which the energy used at the ground work stage is 8.24E+08 MJ, this is for soil handling prior to the power plant construction. Energy used for the road construction is amounted to 2.81E+07 MJ, operation and maintenance energy is 3.42E+08 MJ and 2.25E+08 MJ respectively. Transportation energy has been used 1.55E+08 MJ for all materials, reinforcement, hydraulic and electro-mechanical equipment. The largest energy consumption was at the construction stage of the dam and its appurtenant structures, which is amounted to 1.15E+09 MJ. It is estimated to use 9.77E+07 MJ and 3.97E+07 MJ in the production of hydraulic equipment and electro-mechanical equipment. The plant use 0.5 % of its own energy for the daily operation. The total energy consumption within $EROI_{stnd}$ boundaries is 2.86E+09 MJ within 100-year operation as shown in Table A.9.

Table A.9 Total energy expenditure of Kunn multipurpose hydropower plant.

Energy Expenditure Breakdown	Energy (MJ)	Percentage (%)
1. Power usage at site	3.42E+08	11.95%
2. Maintenance	2.25E+08	7.86%
3. Transportation	1.55E+08	5.42%
4. Groundwork phase	8.24E+08	28.79%
5. Preparation stage	2.81E+07	0.98%
6. Construction stage	1.15E+09	40.20%
7. Hydraulic equipment	9.77E+07	3.41%
8. Electro mechanical equipment	3.97E+07	1.39%
Total Process Energy Input	**2.86E+09**	100.00%

$EROI_{stnd}$ Results for Kunn Multipurpose Hydropower Plant

The $EROI_{stnd}$ is the ratio of direct energy inputs and indirect energy inputs to the power plant, thus in the case of Kunn multipurpose hydropower plant, this will include all the above-mentioned energy expended. The total process energy input of the plant in its 100 year lifetime is 2.86E+09 MJ resulted in $EROI_{stnd}$ values of 24.

Energy Payback Time (EPT) Calculation

EPT for Kunn Chaung hydropower plant is calculated based on the Equations (5.72), (5.73) and (5.74) described in Section 5.3 in Chapter 5. Hence, to calculate EPT values, the annual electrical output is divided by annual (total) energy input based on the life time of the power plant. Thus, it is needed to calculate Energy Output and Energy Input values for first year up to 100 years.

(1) Energy Output Calculation for EPT

As stated information in Table A.2, the Electrical Output of the plant can be calculated for the first year up to 100 year.

(2) Energy Input Calculation for EPT

Energy input calculation for EPT is also used the eight parts which have been done for $EROI_{stnd}$ calculations those being: (1) Power usage at site (2) Maintenance (3) Transportation (4) Groundwork phase (5) Preparation Stage (6)

Construction stage (7) Hydraulic Equipment, and (8) Electro Mechanical Equipment.

For the calculation of EPT value for the first year (year 1), the embedded energy amount of Power usage at site for the first year is calculated, and then calculate the energy invested amount in maintenance for the first year. However, the energy used in transportation, groundwork phase, preparation stage, construction stage, hydraulic equipment and electro mechanical equipment are not needed to be calculated again for first year Those values are the same values which have done for $EROI_{stnd}$ calculation because the amount of energy invested in all those stages are equally involved throughout the plant' lifetime (for instance, the embedded energy used in transportation for the first year = the embedded energy used in transportation for the second year = third year, and so on, up to 100 year).

(3) EPT Calculation

After those two steps, calculate EPT value by dividing Energy Output and Energy Input from the first year to 100 year.