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Reduction of Carbon Dioxide (CO_2) in the Atmosphere, Hydropower as a Viable Renewable Energy Resource

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ABSTRACT

The development of energy from this renewable resource is a very important step in the reduction of CO_2 emissions in the atmosphere that is a major contributor to global warming. Adaptation of non-hydropower renewable energy has been slow for complex reasons including the cost relative to conventional fossil fuel energy, the uncertainty of deploying new technologies, and the technical challenges of storage and distribution. The growing focus on mitigating climate change however, provides a new incentive for those concerned about reducing global carbon footprint to invest more in hydropower production. Key challenges for hydropower include continued development of new technologies to harness hydrokinetic energy, and mitigate environmental impacts associated with larger-scale conventional hydropower generation.

This review paper evaluates the potential of hydroelectric power as a near-zero CO_2 emitter in the reduction of global carbon footprint. Also reviewed are some features of a typical hydropower plant and those of the three main hydropower stations in Nigeria that may assist in encouraging more investment in such facilities in the interest of our environment.

KEYWORDS: Hydropower, CO_2 emissions, global warming, carbon footprint, environment.

1. INTRODUCTION

Atmospheric levels of carbon dioxide (CO_2) have increased steadily since the beginning of the industrial revolution and it is expected to increase even more rapidly as the global economy grows. Significant climate changes are very likely associated with increased atmospheric concentrations of certain gases, most significantly CO_2. The human and ecological cost of climate changes forecast in the absence of mitigation measures is sufficiently large, and the time scales of both intervention and resultant climate change response are sufficiently long (ASME, 2009). All electricity generation technologies generate carbon dioxide and other greenhouse gases. Emissions can be direct-arising during the operation of the power plant, and indirect- arising during other non-operational phases of the life cycle. Fossil fuelled technologies (coal, oil, gas) have the largest carbon footprints, because they burn these fuels during operation. Non-fossil fuel based technologies such as hydropower, wind, photovoltaic (solar), biomass, and wave/tidal are often considered as 'low carbon' or 'carbon neutral' because they do not emit CO_2 during their operation (Postnote, 2006).

Hydropower is a renewable, non-polluting and environment friendly source of energy. It is perhaps the oldest energy technique known to mankind for conversion of mechanical energy into electrical energy and it represents the use of water resources towards inflation free energy due to absence of fuel cost. Hydropower contributes around 22% of the world electricity supply generated and the total potential of the World's small hydropower alone is about 780,000 MW out of which 50,000 MW has already been utilized (Mehra et al., 2007).

2. Global Warming and CO_2 Emissions

Although the science of global warming has been in place for several decades, only in the last decade and a half has the issue moved clearly into the public sphere as a policy issue. Following early scientific discoveries on the 'greenhouse effect' at the end of the nineteenth century, the basic physical science underlying the theory and empirical evidence for global warming as a direct result of CO_2 emissions in the atmosphere was supported through wartime and post-World War II scientific enterprise to master nuclear weaponry and understand how nuclear radiation and fallout would travel throughout the atmosphere and terrestrial and marine environments (Jan et al., 2007).

Recent scientific observations about the impact of human activities on the climate did not initially raise much concern about the greenhouse effect. First, scientists had identified many natural and human-induced

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influences on global climate, including sunspots and water vapour in the atmosphere to ocean circulation, thus greater influence by human beings were considered not too significant when compared with forces of nature. Second, scientific enterprise was overwhelmingly focused on wartime issues, such as nuclear physics, weaponry and weather modification. Third, the prevailing scientific belief was that any climate change resulting from human-made emissions was likely to be benign, relatively small and easy to control with the vast technological means available to us (Jan et al., 2007).

In a 1965 scientific meeting hosted by the National Center on Atmospheric Research, MIT scientist Lorenz showed that the climate may not be a stable system or 'deterministic' system, while other scientists advanced theories about how radical climate change had occurred at the close of the last ice age, 11 000 years ago. Scientists showed that climate had warmed 5-10^{0}C in less than 1000 years, marking the end of this ice age (Jan et al., 2007).

Preventing catastrophic and irreversible damage to the global climate ultimately requires a major de-carbonization of the world energy sources. On current trends, energy-related emissions of CO_2 and other greenhouse gases will rise inexorably, pushing up average global temperature by as much as 6^{0}C in the long term hence, strong and urgent action is needed to curb these trends (Malyshev, 2009).

The projected rise in emissions of greenhouse gases in the Reference Scenario of the World Energy Outlook point to continuing growth in emissions of CO_2 and other greenhouse gases indicating that global energy-related CO_2 emissions rise from 28 gigatonnes (Gt) in 2006 to 41 Gt in 2030-an increase of 45%. World greenhouse-gas emissions, including non-energy CO_2 and all other gases, are projected to grow from 44 Gt CO_2-equivalent in 2005 to 60 Gt CO_2-eq in 2030, an increase of 35% over 2005 according to IEA, 2008b (Malyshev, 2009) as shown by the greenhouse gas trajectories in Figure 1 below.

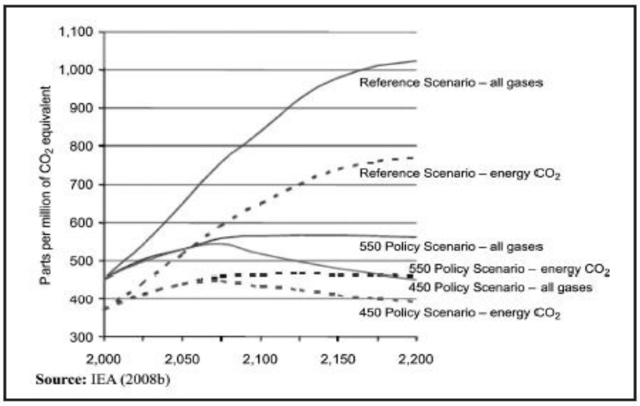

Figure 1: Greenhouse gas trajectories by scenario [Source: (Malyshev, 2009)]

3. **Renewable Hydroelectric Power**

Hydropower is the world's largest renewable source of electricity, generating 3.035 TWh in 2006, around 16 percent of total electricity (Malyshev, 2009). The unexploited potential is large, particularly in developing countries. However, although hydropower is a key mitigation option, climate change may have an overall net negative impact on water resources and therefore affect its future generation potential. Growing concerns about competition for water supply, as well as other environmental and social concerns, may constrain some project developments (Malyshev, 2009).

Reducing GHG emissions requires assertive action in all energy sectors. For electricity production, there are essentially three methods to reduce CO_2 emissions:

i. Use fuels with lower or near-zero CO_2 emission per unit of electricity produced such as hydropower
ii. Increase the efficiency of both electricity production and end-use
iii. Carbon dioxide Capture and Storage (CCS) method.

These methods are applied in electricity generation by increasing the use of renewable energy sources and reducing the carbon footprint of fossil power. Carbon footprint is the total amount of CO_2 and other greenhouse gases, emitted over the full life cycle of a process or product. It is expressed as grams of CO_2 equivalent per kilowatt hour of generation (gCO_2eq/kWh), which accounts for the different global warming effects of other greenhouse gases. Renewable electric technologies include hydropower, wind, solar (concentrating solar thermal power and photovoltaic), geothermal, waste-to-energy and combustion of biomass.

In 2008, Energy Information Agency reported that conventional hydroelectric power is the largest source of renewable electricity in the U.S., generating 7.1 percent of electricity produced in 2006 by the electric power sector. Wind, solar, geothermal, biomass, and non-traditional hydrokinetic (wave/tidal/currents) account for only a small fraction of the electricity produced worldwide despite the availability of technologically advanced systems (ASME, 2009).

Hydroelectric dams have long been one of the mainstays of conventional energy development policy, promoted throughout the world as a key element of the industrialization era. Over the past several decades, however, hydro dams have been subject to scathing critique on a variety of grounds, led primarily by grassroots groups of dam-affected peoples and transnational environmental Non Governmental Organizations (Robert, 2010). In addition to displacing millions of people worldwide, frequently failing to deliver expected benefits (irrigation, flood control, electricity production etc.), and tending to significantly overrun initial cost projections, large dams are seen to precipitate a variety of negative ecological impacts, including: the reduction of bio-diversity, impeded fish migration, reduced water quality (both in the reservoir and downstream), increased diseases (malaria, schistosomiasis, river blindness etc), increased downstream erosion, flood danger, reduced floodplain soil replenishment and loss of farmlands and livestock.

However, adaptation of non-hydropower renewable energy has been slow for complex reasons including the cost relative to conventional fossil fuel energy, the uncertainty of deploying new technologies, and the technical challenges of storage and distribution. At present, worldwide efforts to encourage growth in installed renewable capacity are driven by government policies and incentives (ASME, 2009).

In 1995, the US Department of Energy pronounced that hydropower plants produce no carbon dioxide and no air emissions at all. As a result, the growing focus on mitigating climate change provides a new incentive for those concerned about reducing their carbon footprint to invest in hydropower production (Robert, 2010).

In 2000, the International Energy Agency Hydropower Agreement produced a report asserting that hydro projects should receive subsidized loans from aid agencies as a payback of the global community for the protection of nature and the world climate. This incentive to invest in hydro power is enhanced dramatically by the Kyoto Protocol, particularly its Clean Development Mechanism (CDM), which seeks simultaneously to reduce greenhouse gas emissions in some countries and spur sustainable development in less-developed nations. Under the CDM's provisions ACM0002, the ''Consolidated baseline and monitoring methodology for grid-connected electricity generation from renewable sources," for large projects, and AMS-ID, "Grid connected renewable electricity generation," for smaller ones, hydroelectric dams can be used as offset projects to compensate for emissions from other industrial sources, on the assumption that dams "reduce or displace fossil energy" (Robert, 2010).

In June 2006, the UK Government's Department of Trade & Industry (DTI) published its Energy Review, assessing progress towards its policy goals set in the 2003 White Paper. However, the broader rationale was also to consider options for the UK's future energy mix in the face of two long-term challenges - climate change and energy security. The review concluded that in order to meet these challenges, diversity of energy supply is essential. In this context, the future role of all kinds of energy supply is currently being debated in the UK (Postnote, 2006).

The objective of a hydropower scheme is to convert the potential energy of a mass of water, flowing in a river with a certain fall into electrical energy at the lower end of the scheme, where the powerhouse is located (ESHA, 2004).

Power generation and distribution in Nigeria is the responsibility of the Power Holding Company of Nigeria (PHCN) and presently it has, eight power stations consisting of three hydro-power stations at Kainji (760MW), Jebba (540MW) and Shiroro (600MW) and five fossil fired thermal plants at Egbin (1320MW), Ijora (60MW), Sapele (1020MW), Ugheli (600MW), Ajaokuta (110MW), Oji River (20MW) and Afam (720MW). Both Kainji and Jebba hydropower reservoirs were constructed across the River Niger (Kainji upstream Jebba) and dependent upon the combination of flows from the tributaries of the River Niger while Shiroro plant is on river Kaduna (Isa et al., 2007). The characteristics of the three major hydropower stations in Nigeria are depicted in table 1 and the features of a typical Hydropower Plant are discussed in the following sections:

Table 1: Features of three major hydropower stations in Nigeria (Source: Pamphlets)

Features	Jebba	Kainji	Shiroro
Number of turbines	6	8	4
Turbine propeller type	Kaplan (Fixed Blade)	Kaplan (Adjustable), Propeller(Fixed Blade)	Francis
Diameter of penstock	10m	9.7m	6.3m
Net head (rated)	27.6m	29.5m	97m
Net head (Maximum)	29.3m	38.1m	108.1m
Turbine speed	93.75 rpm	115.4rpm	150rpm
Power factor	0.85	0.85	0.85
Power output (Rated)	578.4MW	760MW	600MW
Power output (Feb. 2010)	300MW	455MW	300MW
Year of commissioning	1985	1968	1990

3.1 **Powerhouse**

The role of the powerhouse is to house and protect the electromechanical equipment that converts the potential energy of water into electricity. The number, type and power of the turbo-generators, their configuration, the scheme head and the geomorphology of the site determine the shape, size and the location of the building.

3.2 **Turbines**

The purpose of a hydro turbine is to transform the water potential energy to mechanical rotational energy. The potential energy in water is converted into mechanical energy in the turbine, by one of two fundamental and basically different mechanisms:

i. The water pressure applies a force on the face of the runner blades, which decreases as it proceeds through the turbine. Turbines that operate in this way are called reaction turbines. The turbine casing, with the runner fully immersed in water, must be strong enough to withstand the operating pressure. Francis and Kaplan turbines belong to this category (ESHA, 2004).
ii. The water pressure is converted into kinetic energy before entering the runner. The kinetic energy is in the form of a high-speed jet that strikes the buckets, mounted on the periphery of the runner. Turbines that operate in this way are called impulse turbines. The most common impulse turbine is the Pelton turbine. The hydraulic power at disposition of the turbine is given by (ESHA, 2004):

$$P = \rho Q.gH \tag{1}$$

ρ = water specific density (kg/m^3)

Q = discharge (m^3/s)

g = acceleration due to gravity (m/s^2)

H = net Head (m)

The mechanical output of the turbine is given as:

$$P_m = P.\eta \tag{2}$$

η = turbine efficiency

3.2.1 **Francis turbine**

Francis turbines are reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. In this turbine the admission is always radial but the outlet is axial. Their usual field of application is from 25m to 350m head.

The water enters the turbine by the spiral case that is designed to keep its tangential velocity constant along the consecutive sections and to distribute it peripherally to the distributor. The mobile guide vanes control the discharge going into the runner and adapt the inlet angle of the flow to the runner blades angles. They rotate around their axes by connecting rods attached to a large ring that synchronize the movement of all vanes. The runner; usually made of stainless steel transforms the hydraulic energy to mechanical energy and returns it axially to the draft tube (ESHA, 2004).

3.2.2 **Kaplan and propeller turbines**

Kaplan and propeller turbines are axial-flow reaction turbines; generally used for low heads from 2m to 40m. The Kaplan turbine has adjustable runner blades and may or may not have adjustable guide-vanes. If both blades and guide-vanes are adjustable it is described as "double-regulated". If the guide-vanes are fixed it is "single-regulated". Fixed runner blade Kaplan turbines are called propeller turbines. The double regulation allows, at any time, for the adaptation of the runner and guide vanes coupling to any head or discharge variation. It is the most flexible Kaplan turbine that can work between 15% and 100% of the maximum design discharge. Single regulated Kaplan allows a good adaptation to varying available flow but is less flexible in the case of important head variation. They can work between 30% and 100% of the maximum design discharge (ESHA, 2004).

The type, geometry and dimensions of the turbine will be fundamentally conditioned by the following criteria: net head, discharges through the turbine and rotational speed. Head is the elevation difference between the source of the water and the turbine, or the total vertical drop. Head can be measured several ways using a sight level, water level, topographical maps, or a GPS unit. A simple uphill survey method using two people and a sight level is a cost effective way to measure the head.

The gross head is the vertical distance that the water falls through in giving up its potential energy. It is measured between the upper and lower water surface levels at the intake and tailrace. Sites where the gross head is less than 10m are classified as “low head”, from 10m to 100m as “medium head” and above 100m as “high head”.

In high head projects the gross head can be measured directly from the maps. In low head schemes instead, field measurements of the gross head for different flow rates are usually necessary. These measurements should be carried out using surveying topographical techniques. The net head is the actual head seen by a turbine which is slightly less than the gross head due to losses developed along the path, from the diversion to the tailrace, when transferring the water into and away from the machine (Escobar, 2007). Different turbines and the range of head they can accommodate are shown in table 2 below:

Table 2: Range of Heads [Source: (ESHA, 2004)]

Turbine type	Head range (m)
Kaplan and Propeller	2 < H < 40
Francis	25 < H < 350
Pelton	50 < H < 1300
Crossflow	5 < H < 200
Turgo	50 < H < 250

A single value of the flow has no significance. It is necessary to know the flow regime, commonly represented by the Flow Duration Curve that relates the inflow and discharge of the hydro dam. The rated flow and net head determine the set of turbine types applicable to the site and the flow environment. The final choice between one type of turbine and another will be the result of an iterative calculation taking into accounts the investment costs and the yearly production output.

Rotational speed of a turbine is directly linked to its specific speed, flow and net head. In turbine selection consideration is given to whether the generator will be coupled directly or through a speed increaser to the turbine, so as to achieve the synchronous speed.

3.3 Generators

Generators transform mechanical energy into electrical energy. Although most early hydroelectric systems were of the direct current variety to match early commercial electrical systems, nowadays only three-phase alternating current generators are used in normal practice (ESHA, 2004). Depending on the characteristics of the network supplied, these types of generators are employed as:

i. **Synchronous generators:** They are equipped with a DC electric or permanent magnet excitation system (rotating or static) associated with a voltage regulator to control the output voltage before the generator is connected to the grid. They supply the reactive energy required by the power system when the generator is connected to the grid. Synchronous generators can run isolated from the grid and produce power since excitation is not grid-dependent. The fundamental characteristic of synchronous generators is that their rotor speed is always locked in with and exactly proportional to the frequency of the interconnected power grid.

ii. **Asynchronous generators:** They are simple squirrel-cage induction motors with no possibility of voltage regulation and running at a speed directly related to system frequency. They draw their excitation current from the grid, absorbing reactive energy by their own magnetism. Adding a bank of capacitors can compensate for the absorbed reactive energy. They cannot generate when disconnected from the grid because they are incapable of providing their own excitation current. However, they are used in very small stand-alone applications as a cheap solution when the required quality of the electricity supply is not very high.

3.4 Exciters

The exciting current for the synchronous generator can be supplied by a small DC generator, known as the exciter, driven from the main shaft. The power absorbed by this DC generator amounts to 0.5% - 1.0% of the total generator power. Nowadays a static exciter usually replaces the DC generator, but there are still many rotating exciters in operation.

A static exciter is a grid connected rectifier that provides DC current to the generator field coils instead of the rotating exciter. The voltage and power factor control works in the same way as with the rotating device. Static exciters are robust, easy to maintain and have a high efficiency.

3.5 Turbine control

Turbines are designed for a certain net head and discharge. Any deviation from these parameters must be compensated for by opening or closing the control devices, such as the wicket-gates, vanes, spear nozzles or valves, to keep either the outlet power, the level of the water surface in the intake, or the turbine discharge constant.

In schemes connected to a grid network, speed (frequency) regulation is normally accomplished through flow control; once a gate opening is calculated, the actuator gives the necessary instruction to the servomotor, which results in an extension or retraction of the servo's rod. To ensure that the rod actually reaches the calculated position, feedback is provided to the electronic actuator. These devices are called 'speed governors' (ESHA, 2004).

A governor is a combination of devices and mechanisms, which detect speed deviation and convert it into a change in servomotor position. A speed-sensing element detects the deviation from the set point; this deviation signal is converted and amplified to excite an actuator, hydraulic or electric, that controls the water flow to the turbine. In a Francis turbine, where there is a reduction in water flow there is the need to rotate the wicket-gates. For this, a powerful governor is required to overcome the hydraulic and frictional forces and to maintain the wicket-gates in a partially closed position or to close them completely.

3.6 **Substation**

The water-to-wire system usually includes the substation. A line breaker must separate the plant from the grid in case of faults in the power plant. Power and current transformers metering are essential at the connecting link between the plant-out conductors and the take-off line to the grid. The standard generation voltages of 400V or 690V allow for the use of standard distributor transformers as outlet transformers and the use of the generated current to feed into the plant power system (Escobar, 2007).

Particular care should be paid to the connection capacity of the grid. A connection to a saturated grid is more expensive than a simple one, due to the fact that in the first case the grid will have to be reinforced to accept further connections. Moreover, to give a right estimate of the connection cost, it is necessary to know which connection has to be planned (high or low voltage) and the distance to the connection.

4. **Conclusion**

Achieving energy efficiency is a long-term worldwide initiative that should involve efforts from all concerned and there is no known single solution for reducing CO_2 emissions in the atmosphere. Development and implementation of policies that will achieve lower carbon life-cycle emissions require strategies that address lifecycle attributes of renewable energy resources such as hydropower. Pumped storage hydropower may provide critical storage capacity for intermittent and non-peak renewable generation from wind, solar, and ocean technologies. Key challenges for hydropower include continued development of new technologies to harness hydrokinetic energy, and mitigate environmental impacts associated with larger-scale conventional hydropower generation.

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