# HYDROELECTRIC CASCADE PLANTS IN THE OMO BASIN IN ETHIOPIA

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**INTRODUCTION** Ethiopia has abundance of highland rivers providing a large energy potential in the form of hydroelectric power. Power planning studies have estimated that Ethiopia's hydroelectric potential is in the order of 30,000 *MW* (Hailu, 1998) greatly in excess of foreseeable domestic energy demand. Several plants are currently under design and/or construction to make the best use of this valuable energy source. This paper deals with the first and second stage of the Gibe hydroelectric cascade on the Omo river basin, in the South-West of Ethiopia.

The current cascade scheme is based on the energy demand forecast of the late '90s where only about 360 MW of the hydropower potential was exploited. The Ethiopian power system was essentially based on relatively few medium size hydroelectric plants as indicated in the following table :

Table 1

The Ethiopian energy production at 1997

| | Capacity (MW) | | Energy (GWh/y) | |
|---|---|---|---|---|
| | Installed | Dependable | Average | Firm |
| Hydroelectric | 360.2 | 331 | 1669 | 1279 |
| Thermal | 6.5 | 5.5 | 35 | 35 |
| Total | 366.7 | 336.5 | 1704 | 1314 |

The ratio between the firm and average producible energy was in the order of 0.77. The secondary energy is concentrated in the rainy season, when most of the hydroelectric plants have excess generation capacity, not used by the system.

Since the late 90's, through the implementation of a comprehensive program of economic reform, the national economy has been growing, lifting the population from severe poverty. To sustain such growth adequate infrastructures and energy supplies have been foreseen.

At the time of the project design, EEPCO forecast an increase of the peak power demand of 250-300 *MW*, and of at least 1,100 to 1,200 *GWh/y* in terms of energy, within the year 2002. In the following five years, within 2007, a minimum of 300 *MW* of additional dependable capacity and of 1,300 *GWh/y* of additional firm energy availability should be provided to the national grid.

To achieve the targets of the EEPCO (Ethiopian Electric Power Corporation) forecast of 250-300 *MW* increase in the energy demand between 1997 and 2002, the only significant addition was provided by the short term realization of new power plants, such as the Gilgel Gibe system among others planned in the Gibe/Omo basin.

The first two stages of the Gibe cascade development include two power plants, namely the Gibe I and Gibe II. The first plant, Gibe I or Gilgel Gibe HPP, is a conventional hydroelectric power plant with a capacity of 184 *MW*. Started in 1986 and completed in 2004 (after being interrupted in the early 90's) is currently the Ethiopia's largest power plant.

The downstream power plant Gibe II will convey the flow, regulated by the Gibe I dam, through a 26 *km* long hydraulic tunnel to the Omo river about 150 *km* downstream of Gibe I dam. This second phase started in 2005 and is scheduled for completion in 2008. The plant will produce about 420 *MW*. When operative the Gibe I and II hydropower system will provide globally about 600 *MW*, which would make considerable contribution to increase the existing energy system.

The power network of the country, including the Gibe cascade plants, is managed by the Ethiopian Electric Power Corporation (EEPCO).

The construction of the Gibe I plant has been carried out by several construction companies, including Salini-Necso for the dam, basing on the design by ENEL-ELC-SP.

Salini Costruttori of Italy is the general contractor for the Gibe II plant with the engineering carried out by SP Studio Pietrangeli.

## GENERAL LAYOUT OF THE SYSTEM

**Project area, location** The Gilgel GIBE system is a purely hydroelectric scheme including two power plants located on the Gilgel Gibe and Omo rivers, about 250 *km* South-West of Addis Abeba and 80 *km* North-East of Jima. The Gilgel Gibe is a tributary of the Great Gibe River, known as the Omo river downstream of the bridge of the Highway Addis Abeba – Jima.

The morphology of the stretch of the Gilgel Gibe river between Asendabo and Deneba was considered suitable for the construction of the reservoir with a capacity sufficient to regulate most of the river flows. The valley is in fact almost flat or slightly hilly. The dam was placed in the downstream stretch, towards Deneba waterfalls where the river banks become steeper. In this way a dam of limited height was sufficient to obtain a reservoir with the required storage capacity.

Going downstream, the river mainly flows northerly into a narrow valley until the confluence with the Great Gibe, which turns South flowing parallel and opposite to the Gilgel Gibe at the short distance of about 25 *km*. The difference in elevation between the two stretches (Gilgel Gibe and Great Gibe/Omo river) is about 500 *m*. This circumstance made particularly attractive to further exploit the hydropower of the stretch of the Gilgel Gibe downstream the first plant, taking advantage of the flow regulation achieved by the upstream reservoir and of the large available head, by means of a tunnel connecting the two rivers.

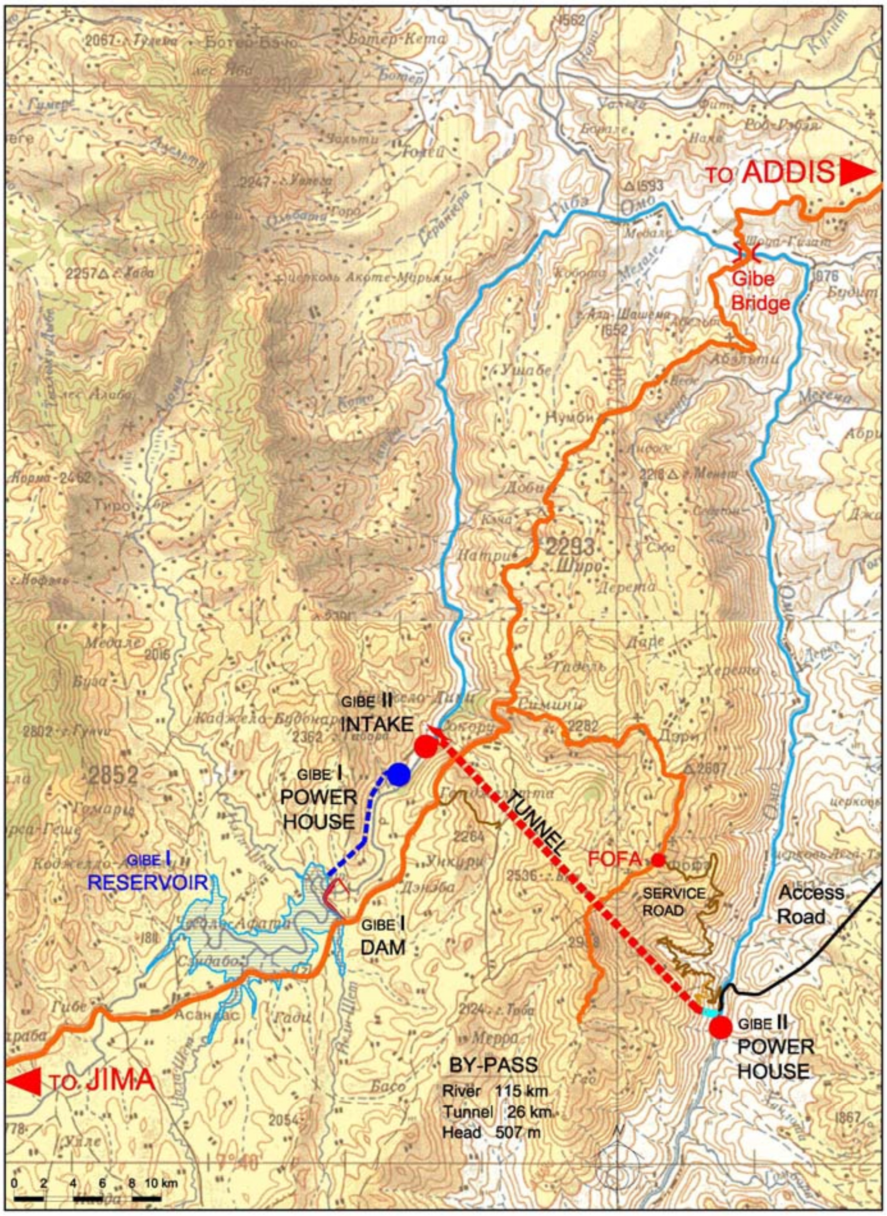


Fig.1. General layout of the hydroelectric system.

**Basic features** The general layout is reported in Fig. 1. The first plant of the Cascade regulates the Gilgel Gibe river with a reservoir of approximately 840 $Mm^3$.

The second plant uses the water discharged by the first one diverting the flows into a waterway that bypasses about 110 *km* of the two rivers, Gilgel Gibe and Omo. The intake is located on the Gilgel Gibe river about 2.5 *km* downstream of the Gibe I outlet. The waterway crosses the ridge between the Gilgel Gibe valley and the Omo valley by means of 26 *km* of tunnel and 1.2 *km* of penstocks. The outdoor powerhouse is located along the Omo river right bank approximately 60 *km* d/s of the Addis Abeba – Jima highway Bridge on the Gibe river.

The aerial views of the hydroelectric systems are reported in Fig. 2, 3 and 4.

Fig.2. The Gibe I dam on the Gilgel Gibe river.

Fig.3. Satellite view of the Gibe I dam and reservoir.
It is possible to see the spillway chute on the left bank.

Fig.4. The Gibe II power house, under construction.

The selection of the general layout of the two cascade plants scheme has been governed by a number of technical and economic considerations, and was substantially influenced by the geological conditions of the area.

In general terms, the following considerations apply:

- The Gibe I dam design was mainly influenced by geological condition of the area. In particular all along the stretch of the river downstream of the Deneba waterfall, the construction of relatively high dam would have been impossible or extremely difficult.
- The downstream plant is fed by the outflow of the upstream powerhouse and of the runoff of the intermediate catchment, which is practically negligible.
- Therefore the storage volume available for the operation of the downstream plant is very little, making mandatory a more or less strictly synchronous operation of the two powerhouses.

Following these criteria the general layout of the cascade scheme was selected. The basic features of the two plants are summarised hereafter:

*a*) Upstream plant:

- reservoir, with a live storage of 657 million $m^3$ and a dead storage of 182 million $m^3$, operating between elevation 1,653 and 1,671 *m a.s.l.*, with an average inflow of 50 $m^3/s$,
- rockfill dam of volume of 2.5 million $m^3$, with a 105,000 $m^2$ impervious bituminous facing, approximately 40 *m* high and 1,600 *m* long,
- gated open chute spillway located on the left abutment and designed for a not routed discharge of 1,450 $m^3/s$ and verified for an exceptional routed flood of 2253 $m^3/s$,
- power intake for 101.5 $m^3/s$; 5.5 *m* of diameter and approx. 9.0 *km* long concrete lined tunnel with terminal surge shaft; underground penstocks and manifold,

- cavern powerhouse equipped with three Francis units of about 60 *MW*; 240 *m* of gross head.

*b*) Downstream Plant:

- daily reservoir with a live storage for daily regulation, operating at elevation 1,431.5 *m a.s.l.*, with an average yearly inflow of 50 $m^3/s$,
- concrete gravity weir 40 *m* high and 170 *m* long, incorporating an ungated spillway on the crest; upstream de-silting weir,
- power intake tower for 101.5 $m^3/s$ on the right bank of the upstream reservoir; 6.3 *m* in diameter and *25.8* km long concrete lined tunnel with terminal surge shaft; underground penstock for the first 100 *m* followed by two outdoor penstocks after bifurcation, final manifold,
- outdoor powerhouse on the right bank of the Omo river, equipped with four 105 *MW* Pelton units.

**Flow and operation** The rated outflow of Gibe I is 101,5 $m^3/sec$ (3 units, 33.85 $m^3/s$ each ). Continuous environmental flow of about 1.3 $m^3/s$ is released downstream of the Gibe I dam. This flow is not diverted by the Gibe II plant and spills downstream the weir together with the entire runoff of the residual catchment area between the two plants, which is about 79 $km^2$, irrelevant if compared with catchment of Gibe I (4225 $km^2$).

In order to avoid energy losses due to the spilling over of the weir in addition to the environmental release, the rated flow of the second plant is the same as the first one, i.e. 101,5 $m^3/s$ and the two plants in cascade operate in a synchronous manner according to a single Operation Rule. As a consequence the Power Output of each plant will be constantly in the ratio of the respectively net heads, apart the minor difference due to electromechanical equipment efficiency.

It should be noted that, being the gross head over the two powerhouses different, unequal turbines, both in type and number, were chosen. Nonetheless a synchronous operating rule should be followed.

**Energy** According to the reservoir operation studies and the flow duration curve the installed capacity and energy production of the Gibe I plant is as follows:

- 184 *MW* Maximum power (considering three units operating at maximum discharge),
- 722 *GWh/year* Average Annual Energy produced,
- 622 *GWh/year* Firm Energy produced,

The Plant Factor for Gibe I results to be 0.46. As the two plants in cascade will operate in a synchronous manner, the plant factor value of the first stage can be assumed also for the second stage.

With this assumption the following energy production results for Gibe II:

- 420 *MW* Maximum power,
- 1625 *GWh/year* Average Annual Energy produced,

more than double of the energy produced by the Gibe I.

**Dams design** At an early stage, for the Gibe I plant, different types of dams were analyzed from the technical and economical point of view:

- Concrete Gravity dam: this alternative was rejected, given the presence on the right bank of a massive layer of degraded tuff with very poor geomechanical characteristics (high compressibility, low friction angle, abundant clayey matrix) unsuitable for that kind of dam. Moreover the removal of this material would have been a too expensive solution.
- Homogeneous earthfill dam: this alternative was rejected because the material available at the site was of very poor characteristics, requiring very flat embankment slopes.
- The studies were thus concentrated on the most viable rockfill dam solution. In fact, rockfill material con be readily obtained by quarrying the basalt flows of the area. As no suitable material for an impermeable core was available at the site, preference was given to an upstream bituminous impervious facing, more flexible, quicker to build, easier to repair and less expensive than a concrete one.

The location of the Gibe II weir is a narrow gorge with rocky, steep slopes. The proposed weir is a classical concrete gravity structure, slightly arched in plan, with :

- crest level at 1439 *m a.s.l.,*
- total crest length of 140 *m*,
- maximum foreseen height above foundation level of 49 *m*.

A typical triangular section has been adopted with an upstream face sloping 0.10/1 and a downstream face sloping 0.75/1. The large spillway structure is located on the central blocks.

In order to face the silting problem of the reservoir, specific solutions have been adopted including an upstream desilting weir and a special design of the bottom outlet and of the intake structure (with stoplogs).

**Underground excavations**

Given the morphology and the geological characteristics of the area of Gibe I, underground solutions were adopted for the powerhouse and relevant facilities, surge shaft and waterway. The waterways include a 5.5 m diameter concrete line tunnel, 8,780 *m* long. The cavern is 83 *m* long and 41 *m* high, and houses three generating units, the erection bay and the service building. The arrangement with lateral erection bay was selected, which allows to reduce the width of the cavern. The excavations, of the tunnel and cavern, were carried out with the conventional drill and blast method.

For the 26 *km* long tunnel of Gibe II, during the preliminary design phase four different layouts were considered (named A,B,C,D). All the alternatives had the same inlet in the Gilgel Gibe river whereas the outlets in the Omo river were spread over about 11 km.

A cost-benefit analysis was carried out to compare the different layouts. The first considered layout was the waterway having the shortest route. If the outlet is moved upstream, the waterway total length remains approximately constant whereas the design head decreases. Therefore the cost-benefit relationship worsens. Differently moving the outlet downstream, costs increase with the waterway total length, but also the design head and consequently the energy produced increases. The most promising alternatives were therefore selected between the layout “C” and “D”.

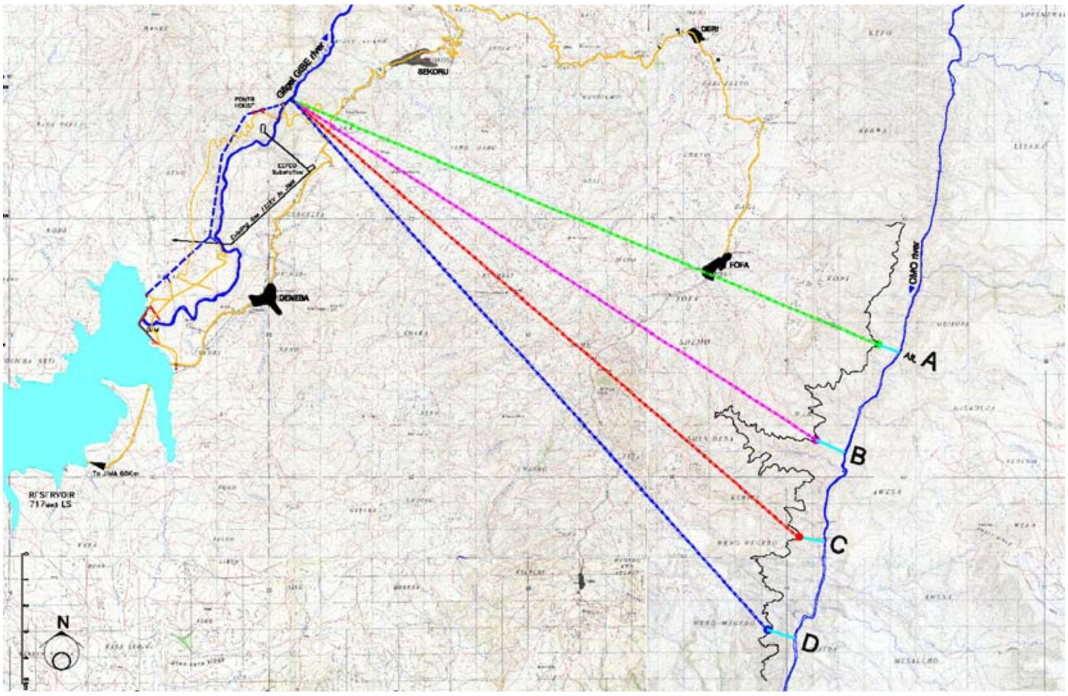


Fig.5. Gibe II power waterway alternative layout

The excavation of the 26 *km* long tunnel with a diameter of 7 *m* for Gibe II is carried out mostly with two TBM (Tunnel Boring Machines) moving contemporary from the upstream and downstream side. An upstream and downstream trunk (~250 *m* long) were excavated with traditional drill and blast method. At the end of this sections the launching chambers (20 *m* long) were assembled (Fig. 6). Then the TBMs started the excavations from the launching chambers up to the dismantling chamber, located approximately in middle of the tunnel. The tunnel slope is 1.605 *m/km*. The elevation of the tunnel is about 1410 *m a.s.l.* and has an overburden between max. 500 *m* and 1200 *m*. A precast segmental lining system was chosen.

Fig.6. Gibe II tunnel - Launching chamber of the TBM

## BENEFITS AND IMPACT ASSESSMENT

**Benefits** It is clear that the realization of the Gilgel Gibe project provides firstly a great benefit at national level in terms of power generation, but also minor benefits are expected at regional and local level.

At national level the project helps the country to meet its rapidly increasing electrical energy demands. The project will eventually produce an energy surplus that can be exported to neighbors, thus earning foreign exchange. Economic expansion will occur as a result of increased electricity supply.

At regional level, the project will provide the source for developing the rural electrification program which will contribute to improve socio-economic conditions.

At local level, a direct benefit derives from employing local people for the construction of the plants. For the already completed Gibe I about 4000 locals were employed. Moreover workers were given the opportunity of training and learning new jobs skills that can be transferred elsewhere upon termination of the project. Additional economical benefits are expected as a result of direct project spending for local goods and services and the local entrepreneurial development.

The presence of the reservoir will certainly reduce the frequency and the peaks of the floods. However downstream the Gibe I plant the river mostly flows into a narrow canyon and no significant infrastructure subject to risks during floods can be found. Therefore, no relevant benefits for flood mitigation is achieved by the project.

**Environmental and social impacts** On the other hand it must be considered that some important environmental and social impacts affect the area during and after the construction of the hydroelectric system. Most of them have been fully mitigated with suitable countermeasures.

EEPCO prepared a comprehensive plan for the land and crop compensation and the resettlement of the about 3,000 people, who have been dislocated as a consequence of the construction of the Gibe I plant. This plan was developed in the policy framework set up by EEPCO to provide guidelines in mitigating adverse social impacts to the projects of the national programme for the power generation improvement (EEPCO, 2006).

For the construction of the Gibe II power plant, on the contrary, no resettlement is required because of the very limited dimension of the reservoir. In fact the stretch of the Gilgel Gibe downstream Gibe I plant to the confluence with the Great Gibe river flows in a narrow valley where no significant infrastructure are located. This makes the environmental and social impact of the Gibe II plant very little.

Nonetheless there are some environmental impacts that cannot, or only partly, be mitigated such as the elimination of riverine forest and along with it the habitat for a variety of fauna in the area of the Gibe I reservoir and buffer zone (~300 *ha*), as well as the alteration of the river regime downstream of the dam (for a distance of 16 *km*) that will affect the aquatic community. On the other hand it can be assumed that the reservoir will develop its own system over time thus offsetting some of the biodiversity loss. Total loss of water to Lake Turkana are estimated to be only 0.17% as a result of evaporation from the reservoir, having a negligible effect on the aquatic communities on the Omo River.

**CONCLUSIONS** The exploitation of hydropower potential has been recognized by the Ethiopian Government as a key issue in the economic development of the country. In spite of its great hydropower potential, less than 3% is exploited at present. The EEPCO forecasting of power demand, at short and medium term, made necessary the planning and realization of new hydropower plants.

The Gibe I – Gibe II hydroelectric system is a starting point in the development of the Gibe-Omo hydropower potential. The system is a cascade scheme of two power plants on the Gilgel Gibe river, with a capacity of 184 *MW* and 240 *MW* respectively. The total annual energy production of the two plants is about 2350 *GWh*. Gibe I has been already completed and is presently fully operational. Gibe II is under construction and is scheduled to be operational by 2008.

Gibe I is a conventional hydroelectrical power plant with a large dam that regulates the Gilgel Gibe river creating a reservoir of 840 $Mm^3$. The second plant, Gibe II conveys the water discharged by the first one, having a gross head of 505 *m* created by an underground waterway that by-passes about 110 *Km* of the two rivers (Gilgel Gibe and Omo).

Gibe II has an intake reservoir negligible for regulation purposes, therefore, in order to avoid energy losses due to the spilling of water downstream, the two plants operate synchronously and the Power Output of each plant is constantly in the ratio of the respectively net heads.

The dam design of the Gibe I, approximately 40 *m* high and 1,600 *m* long, was mainly influenced by the geological features of the area: a rockfill dam with impervious bituminous facing was selected. The most relevant works of the Gibe II plant, the long waterway, comprise the 26 *km* tunnel with 7 *m* diameter excavated by means of two TBM machines.

The benefits deriving from the realization of the Gilgel Gibe hydropower system can be *a*) at national level, helping the country to meet its electrical energy demands enhancing socio-economic development; *b*) at regional level, providing the source for developing the rural electrification program; *c*) at local level, employing local people for the construction of the plant, and improving the local entrepreneurial development.

## REFERENCES

EEPCO, *Universal Electricity Access Programme (UEAP), Resettlement/Rehabilitation Policy Framework (RPF)*, (2006).

ENEL/ELC, *Gilgel Gibe Hydroelectric Project – Feasibility Study*, (1998).

Hailu S.S. Hydropower of Ethiopia: Status, Potential and Prospects. *EACE Bulletin*, Vol.1, No.1, (1998).

SP-SALINI, *Gibe II Hydro-electric Project, Level 1 Design - General report* (2004).

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