The Madeira hydroelectric complex - regional integration and environmental sustainability using bulb type turbines

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Introduction

The Madeira Hydroelectric Complex, takes part in a much broader context such as the Initiative for the Integration of the Regional Infrastructure of South America (IIRSA), which congregates efforts of the South-American Governments. The Complex encompasses four hydroelectric power plants, two of them in Brazil, one on the Brazil/Bolivia border and one in Bolivia, as well as a 4.200 km long waterway.

Nowadays, the existence of several rapids on the Madeira River does not allow boat traffic upstream from Porto Velho. The construction of lock gates on all four of the Madeira Complex power plants shall enable the navigation from the outskirts of the Andes, on Peru and Bolivia, to the Atlantic Ocean and, in association with roadways and/or railways, will also provide an alternative route for Brazilian and Bolivian products to the Pacific Ocean.

The present paper intends to discuss the project concepts, developed studies and actions taken to achieve the Complex construction which, by means of increasing the local energy offer and integrating transportation and energy infrastructures, shall improve the government presence and action on the region, organizing regional development, and establishing solid bases for its sustainable development. The Brazilian Plants of Santo Antônio and Jirau, feasibility studies of which have just been concluded, represent the first step towards this Project, and shall increase the Brazilian power supply offer in 6.45 GW. The necessary authorizations for the international plants inventories are on its final negotiation stages, and the studies are expected to begin soon.

Today, the state of Rondônia electrical generation capability can offer about 800 MW, more than half of it based on diesel thermoelectric power plants, not connected to the integrated Brazilian energy transmission system. The construction of the Santo Antônio and Jirau power plants will increase in 9 times the local energy offer. Transmission lines to the states of Acre, Amazonas, and western Mato Grosso, shall spread such offer throughout an area presently deprived of it. Additionally, the connection to the integrated Brazilian energy transmission system will enable it to benefit from the different hydrological regimens all over the country. The Engineering studies were carried out aiming to achieve the smallest possible environmental impact arising from the construction of the power plants. In order to do so it has been sought to disturb the river regimen the least and restrict the reservoirs areas virtually to those already flooded during rainy season. Therefore, the engineering solution adopted was that of low head power plants, respectively 13.90m (Santo Antônio) and 15.2m (Jirau), making use of Bulb Type Turbines which do not require large reservoirs but rather large water volumes and speed, also yielding several advantages related some specificities of the Madeira project.

Fig. 1. Madeira Project Location.

1. Madeira Project

The Madeira Project, besides its enormous technical and environmental challenge, represents an attempt to integrate the Amazon region to the rest of the country, adding its resources to the Nation's assets, improving the government presence and action on the region and, by means of increasing the local energy offer and integrating transportation and energy infrastructures, achieving an organized regional development as well as establishing solid bases for its sustainable development.

The Project encompasses the construction of four hydroelectric power plants on which, the addition of lock gates shall create a 4,225 km long waterway, enabling navigation on the Madeira, Mamoré, Gaporé, Beni, Madre de Dios and Orthon rivers. The Complex power plants are briefly described bellow and its location shown on figure 1:Brazil: Santo Antônio Hydroelectric Power Plant on the Madeira river, with a installed power of 3,150MW and Jirau Hydroelectric Power Plant on the Madeira river, with a installed power of 3,300 MW, Brazil / Bolivia: Bi-national Hydroelectric Power Plant on the Madeira river at the Brazil / Bolivia border, with an appraised nominal power of 3,000MW,

Bolivia: Hydroelectric Power Plant on the Beni river at Cachuela Esperanza, with an appraised nominal power of 600MW.

Presently the feasibility studies of the Brazilian power plants, Santo Antônio e Jirau, have been concluded and are undergoing evaluation for approval by ANNEL, the Government Agency responsible for the electrical energy concessions in Brazil, and its environmental impact report is being evaluated by IBAMA the Brazilian Federal Environment Agency.

The inventory studies of the other power plants shall soon begin, once the multinational processes to obtain the necessary licenses are on their final stages.

Up until now the studies have been carried out by a private-public partnership between CNO - Construtora Norberto Odebrecht, a world wide construction firm, and Furnas Centrais Elétricas S.A., a state owned energy supplier that provides the service for almost 50% of the Brazilian population.

2. Why the Madeira River

In the search for new opportunities the companies have chosen the Madeira River as an interesting investment based on the following aspects:

- Most of the hydroelectric potential of rivers on the south and southeast regions of the Country are either being exploited or have already been studied, mainly because that's where most of the country population and industries are and, consequently the greater energy consumption,
- The Brazilian hydroelectric potential have been evaluated in about 260,000 MW (ref. 7), 52% of which located on the Amazon region, as shown on figure 2, where, at the end of the millennium only about 5% of its available hydroelectric potential was being exploited;
- Presently the region energy supply is provided by several isolated systems, detached from the Brazilian interconnect transmission system, and based mainly on diesel thermoelectric generation;
- The Madeira river has quite a particular hydrological regimen, once both the defrosting on the Andes and the rain on the Amazon region, contribute to its discharge, resulting in the following characteristics:

»The Madeira River has a seasonal water level variation that reaches values of up to 15m, as can be seen on figure 3, where an average hydrological year and the average of the monthly minimum and maximum water levels are presented.

»The Madeira river presents one of the best flow duration curves of the Amazon region, as depicted on figure 4, along with the curves of two other major rivers on the same area, where equivalent discharge values are plotted against their duration;- Although running through flat lands, the Madeira River peculiar

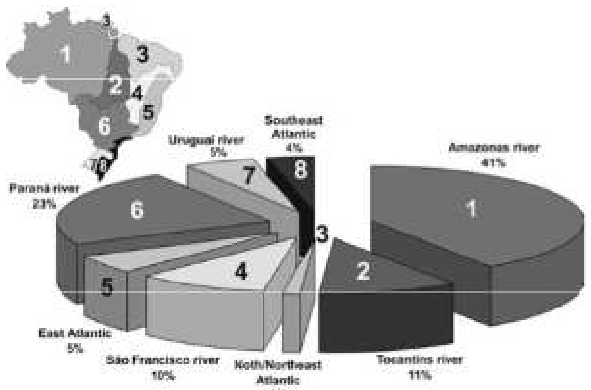


Fig. 2. Brazilian Hydroelectric Potential.

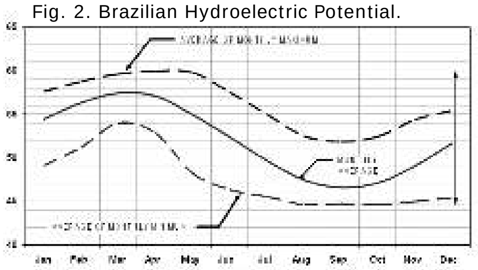


Fig. 3. Madeira River Water Levels
Porto Velho 1967/2004

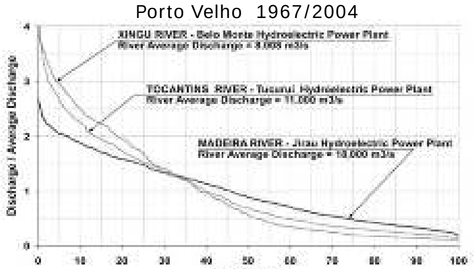


Fig. 4. Madeira River Flow Duration Curve.

Besides the considerable amount of energy to be generated, and the significant improvement on life quality for the inhabitants of the Project surrounding areas, the Madeira Project can bring about several collateral benefits, among others the following:

Connection of the North region to the Brazilian interconnected transmission System, increasing its stability and reliability by taking advantage of the hydrological regimen diversity all over the Country,

» Navigation on over 4,000 km through the Madeira, Mamoré, Gaporé, Beni, Madre de Dios and Orthon rivers,

» Opportunity for infra-structure joint projects involving Peru, Bolivia and Brazil, contributing to South America Integration.

3. Design Directives And Solutions

Any Project on the Amazon region needs to be guided by environmental conscience, which shall be taken into account along with all technical and/or economical aspects.

The inventory as well as the feasibility studies of the Brazilian Power Plants of Santo Antônio and Jirau were developed bounded by rigid design directives, aiming to create a paradigm for Projects on the Amazon Region. The main principles to which the design concepts had to abide are listed bellow

» Non interference with the river vocation

» Navigation route promoting regional integration,

» Hydroelectric energy generation

- Minimum environmental impact:

» Restrict, as much as possible, the reservoir areas to the ones already flooded during the summer season,

» Avoid any interference with international territory,

» Develop civil engineering solutions and equipments to achieve the lesser environmental impact.The Madeira River has an historical vocation for navigation that goes way back to the first Portuguese incursions in the area. Nowadays its 1,056 km long waterway represents an important route for regional integration, transporting people and goods from the city of Porto Velho to the river estuary on the Amazon River, as depicted on figure 5.

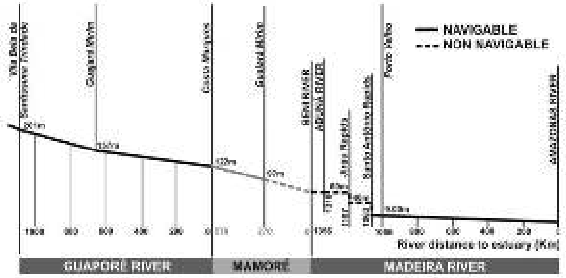


Fig. 5. Madeira River Water Way Today.

In order to avoid any interference with the river navigation, lock gates were added to both power plants, what resulted in an additional benefit once the presence of the reservoir will eliminate the natural obstacles, that emerge during the dry season on the stretch, adding 230 km to the existing waterway,.

A river of such magnitude (average discharge of 18,000 m3/s), even running through flat land, has an enormous hydroelectric potential that could not be wasted.

Complying to the established design criteria an alternative with two low head power plants, as shown on figure 6, was developed, discarding the one on a single power plant, more attractive from the economic point of

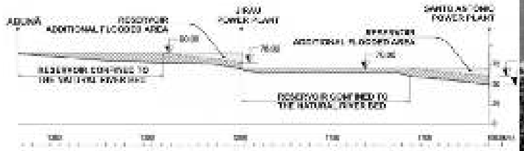


Fig. 6. Alternative On Low Head Power Plants

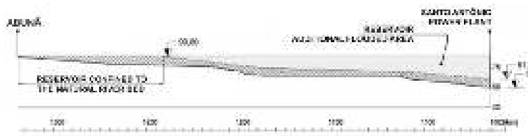


Fig. 7. Discarded Alternative On A Single Power Plant.

Table 1 presented on figure 8 shows a comparison among several Brazilian power plants on the Amazon region, where the ratio between the reservoir flooded area and the plants nominal power reflects the cost / benefit of each plant, demonstrating that the guidelines adopted for the Santo Antônio and Jirau power plants have paid of.

POWER PLANTS ON THE AMAZON REGION(reservoir water level<EL 300m)	Reservoir Flooded Area (km2)	Plant Nominal Power (MW)	Reservoir Area Nominal Power (km2/MW)	Reservoir Maximum Water Level (m)
BALBINA	2,360	250	9,44	50
SAMUEL	584	217	2,69	87
CURUÁ-UNÁ	78	30	2,60	68
MANSO	387	210	1,84	287
LUIZ EDUARDO MAGALHÃES	626	850	0,74	212
TUCURUÍ PHASE1	2414	4,000	0,61	72
TUCURUÍ PHASE2		8,000	0,30	
COROACY NUNES	23,3	67	0,35	120
JIRAU	258 140(*)	3,3	0,08 0,04	90
SANTO ANTONIO	271 110(*)	3,150	0,09 0,03	70

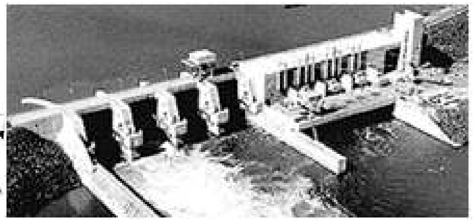
(*) Discouting river area

Fig. 8 Reservoir Area / Nominal Power.

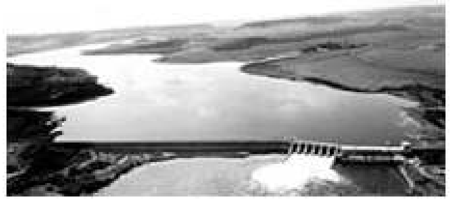
4. The Bulb Type Units

The choice of low head power plants led to the use of Bulb Type Turbines which do not require large reservoirs, but rather large water volume and speed, what the Madeira river can easily provide. Hydro generation in Brazil was first developed on the south-central region of the country, where moderately high, mid and mid-low head sites are available, and to which Francis and vertical-shaft Kaplan turbines are better suited. Therefore bulb type units are not common on major power plants (>30MW) in Brazil, up until now the Brazilian experience with such type of turbine is limited to 3 plants with char

Canoas I Hydroelectric Power Plant:
Nominal head: 16,3 m
Plant Installed power: 85 MW
Number of Turbines: 3 Bulb Turbines
Nominal unit generation power: 27,5 MW



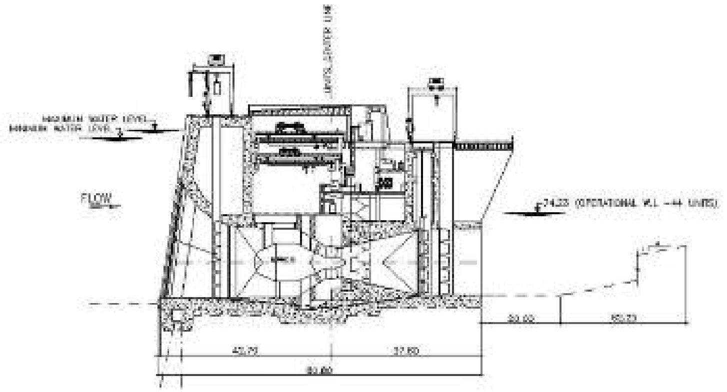
Canoas II Hydroelectric Power Plant:
Nominal head: 14,5 m
Plant Installed power: 72 MW
Number of Turbines: 3 Bulb Turbines



Igarapava Hydroelectric Power Plant:
Nominal head: 17 m
Plant Installed power: 210 MW
Number of Turbines: 5 double regulation bulb turbines
Nominal unit generation power: 43.6MW
Rotation speed : 112,5 rpm
Runner Diameter: 6,0m

Fig. 9 Brazilian Experience on Major (> 30MW) Low Head Power Plants.

A bulb type unit consists basically of a horizontal shaft Kaplan-type turbine runner coupled to a horizontal shaft electric generator. The shaft arrangement may vary somewhat and it may be also slightly slanted. Both turbine and generator are housed within a leak proof steel housing completely immersed in the water flow.
The turbine runner blades diameter estimated for the Jirau and Santo Antônio bulb units are respectively, 7.94 and 8.15 meters.



The bulb technology, since 1935 when first used in Poland, has been in use throughout the world with excellent results, and the foreseen characteristics for the Madeira Power plants turbines are quite similar to many others presently in operation as can be seen

Power Station	Country	Max. Output (MW)	Max. Head (m)	Speed (rpm)	Runner Diameter (m)	No. of Units	Year
Belleville	France	25.9	5.5	84.3	7.5	2	1997
Tadami	Japan	65.8	20.7	100	6.7	1	1989
Murray Lock	USA	19.4	6	62.2	8.41	2	1980
Lingjintan	China	30.83	13.2	78.9	6.9	9	1998
Hongjiang	China	48.10	27.3	136.4	5.46	6	2003
Santo Antonio	Brazil	71.6	13.9	81.8	8.15	44	u/c
Jirau		75	15.2	85.7	7.94	44	

Fig. 11 Bulb Type Turbines Characteristics.

on table 2 presented on figure 11.

The choice of Bulb Type Turbines yields several advantages related to some specificities of the Madeira project, among others the following:
- Each plant will be equipped with 44 units, and such huge number of units will require a careful assembling plan to guaranty the project feasibility. Several are the aspects where the choice of bulb type turbines can contribute to make this huge assembling task easier, among others:
» Even with the need of special devices, it is possible to achieve greater erection speed with Bulb Type Turbines than vertical axis units.
» The erection of turbine and generator can be done in parallel, once the access to turbine and generator recess are independent
» It is possible and usual to pre-assembly many parts at the shop, or even at the erection yard, what enhances the performance of the equipment assembly inside the power house.
- The horizontal axial flux allows a hydraulic circuit simpler and shorter than the one of an equivalent vertical axis unit, what leads to the following advantage
» Reduction of energy losses, what for a low head plant is of paramount importance;
» The simpler and shorter Hydraulic circuit results also in less excavation and faster construction.

- The Madeira river has an average flow of 18,000 m3/s, diverting a river of such magnitude is no easy task. The plant layout was conceived to allow the construction of the power house and spillway without disturbing significantly the river flow, to later divert it to the concluded spillway and power house while the dam is built on the river bed. In such case Bulb Type Turbines suited very well once, besides the smaller excavation, they present reduced width if compared to vertical axis units, resulting in a power house only 972 m long.

- The Madeira river carries a considerable amount of sediments, therefore the bulb turbine capacity to operate as a bottom outlet, at no load up to 70% of nominal flux, enables the discard of sediments accumulated near the powerhouse water intake if necessary.
- The use as bottom outlet possibility for Bulb Type Turbines also increases the dam safety, by adding an additional discharge to the spillway capacity, the latter defined for a flood with 10,000 years recurrence.
- At last the choice of Bulb Type Turbines yields low environmental impact once presents low probability of damage to fishes .

5. Plants Characteristics
Both plants lay-out and river diversion have been conceived to enable power generation during their construction. The first 6 units of each plant shall start generating 44 months after the plant construction begins, and from them on, every month an additional unit shall reach operational status.

	JIRAU POWER PLANT	SANTO ANTÔNIO POWER PLANT
MAIN DAM Type Crest Length	EARTH AND ROCKFILL 1,[illegible] m	EARTH AND ROCKFILL [illegible]
AUXILIAR DAM	575 m (roller compacted)	[illegible]
SPILLWAY Maximum Discharge Number of spans	[illegible] 21	[illegible] 21
POWER HOUSE LENGTH	972.4 m	904.4
NOMINAL WATER HEAD	15.2 m	13.9 m
OPERATIONAL WATER LEVEL Maximum Minimum	9[illegible] m 82.5 m	70 m 70 m
TURBINE Type Nominal Unit Power Number of Units	BULB TYPE TURBINE 75 MW 44	BULB TYPE TURBINE 71.6 MW 44
NOMINAL INSTALLED POWER	3,300 MW	3,150 MW
LOCAL AVERAGE GENERATED ENERGY	[illegible] MW	[illegible] MW
AVERAGE GENERATED ENERGY / INSTALLED POWER	[illegible]	[illegible]

Fig. 12 Power Plants Main Characteristics.

The Power Plants of Jirau and Santo Antônio have similar lay-outs, whose main characteristics are detailed on the table presented on

Figure 12, consisting of 21 spans spillways, water intakes and power houses for 44 turbines, all structures on reinforced concrete and located on the river margins, which shall be built without diverting the river from its natural bed.
When most of the concrete structures are concluded, the construction of rock fill cofferdams will take place on the river main channel, diverting the water to the power house and spillway. The cofferdams later will be incorporate to the main earth and rock fill dam.
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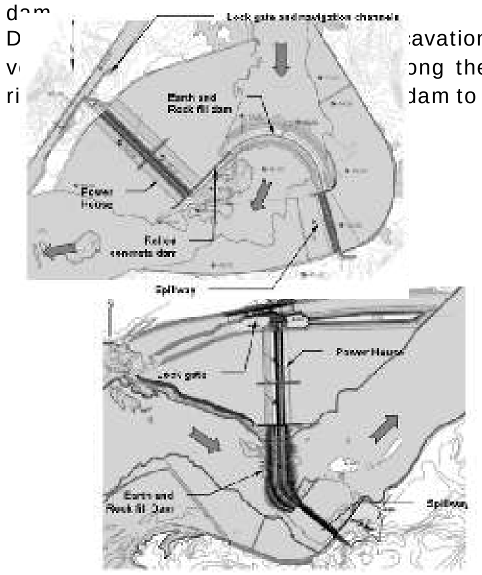


Fig. 13. Layout Jirau Power Plant.
Fig. 14. Layout Santo Antônio Power Plant.

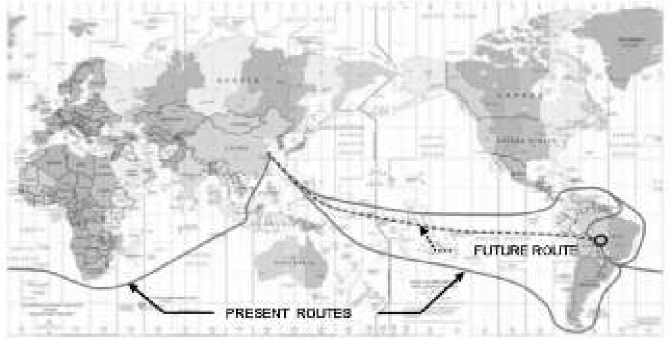
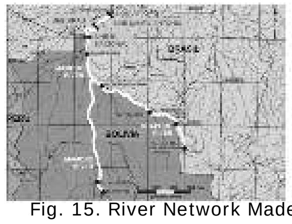


Fig. 18 Routes To The Asian Market.

- Supply of reliable low cost energy to the region,
- Substitution of the diesel based thermoelectric generation by hydroelectric generation,
- Replacement of truck transportation by boat transportation,
- Use of the Itacoatiara port instead of ports on the south and southeast regions,
- Reduction of floating timbers on the Madeira River, increasing navigation safety.
- Connection of the region electrical systems to the Brazilian Interconnected Transmission System,
- Royalties yearly paid to States and cities for the use of the water resource.
The Madeira Project, besides the direct benefits above listed, by providing substantial amount of reliable energy and transportation, both at low costs, shall bring about several indirect benefits, such as:
- Growth and diversification of productive activities to supply the local demand,
- Decrease of the destructive exploitation activities,
- Development of new productive chains,
- Value aggregation to farming and cattle raising activities,
- Reduction of freight costs (use of boat transportation),
- Increase of the region participation on business as well as on national and interna-tional products supply,
- National and continental integration,
- Strengthening of Public Institutions on Peru, Bolivia and Brazil,
- Preservation, control and sustainable use of the natural resources.



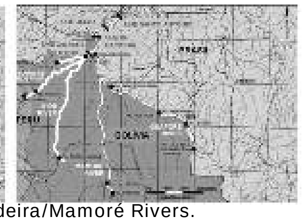


Fig. 15. River Network Madeira/Mamoré Rivers.
Fig. 16. River Network Beni/Madre de Dios/Orthon

RIVER	STRETCH		(Km)
	UPSTREAM	DOWNSTREAM	
Madeira	Rio Beni	Porto Velho	230
Mamoré	Puerto Grether	Rio Madeira	1350
Guaporé	Vila Bela	Rio Mamoré	[illegible]
[illegible]	Puerto [illegible]	[illegible]	[illegible]
Madre de Dios	Puerto Maldonado	Rio Beni	520
Orthon	Puerto Rico	Rio Beni	2[illegible]0
TOTAL			4225

Fig. 17 Added Stretches To The Water Way.

9. Local, Regional and International Discussions
To validate an initiative of such proportions as the Madeira Complex with its multitude of effects and vast influence area, it was necessary to bring the society to the debate. The project had undergone public evaluation on several forums, from meetings with the local society to presentations on international Symposiums and Conferences.
The debates have greatly contributed to better evaluate its benefits and expected impacts, enhancing the design comprehension and earning public credibility especially before the local and regional population as well as respect from the South American community.

10. Conclusion
Environmental conscience with technical responsibility can provide innovative solutions to reduce environmental impacts allowing deve-lopment to reach the regions where nature rules.
The Madeira Project proposes a new approach for construction of hydroelectric power plants on sensible areas, bringing energy, transportation and sustainable development, without compromising the environmental preservation and contributing to control and prevention practices.

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AXIS 1: Mercosul – Chile
AXIS 2: Andes
AXIS 3: Inter-oceans – central
AXIS 4: Amazonas river
AXIS 5: Guyana's
AXIS 6: Peru – Brazil – Bolivia
AXIS 7: Capricorn Tropic
AXIS 8: South
AXIS 9: Paraguay – Parana water way

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