1. EUSUSTEL WP3 Report [hydropower]

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1.1 Introduction

Throughout history the mechanical power of flowing water has been used to grind grain, saw lumber and produce iron and steel structures. The earliest water wheels used the falling water to operate mechanical equipment. After the invention of the water turbine in France in 1827 the first turbines used to produce electrical energy appeared in the 1880's. The earliest stations were constructed to produce electricity locally to a consumer, therefore, their size was adapted to the consumption locally. Later, with the development of larger grids, and with the advance of technology, one could utilize larger rivers and the rating of the turbines increased. Then, mainly due to cheap oil and coal, hydropower was not being developed top a large extent in many corners of the world. In the case of some countries with large hydropower resources the whole industrialization process of the early 1900's was made using hydropower.

The amount of electricity that can be produced by hydro-electricity generation depends on two things:

1. The rate at which the water flows;
2. The difference in height between the top of the dam or reservoir and bottom reservoir, below the turbine. This is called the head of water.

Hydro-electricity generators transform the kinetic energy of moving water into electricity. The system is simple: a continuous flow of water is going through a turbine, induces its rotation and generates mechanical power. This turbine is connected to an alternator which generates electricity which is distributed on the grid.

During the oil crisis of the 1970's there was a renewed interest in hydropower. During this and the following decade the consequences of building large dams were also starting to be heavily debated. One has to remember that most of the dams in the world are not built for the sole reason to produce cheap clean hydropower, but for storing water for agricultural and domestic use, and to avoid excessive damage from flooding.

Today with an increase in the price for the fuel for most thermal plants hydropower is again discussed as an interesting alternative.

Hydropower is today the only renewable power source that contributes substantially to the world power supply (around 19% annually [1]). In Europe, the generating capacity from hydropower is on the increase (1% from 2002 to 2003). The gross potential in the EU-25 countries [2] has been estimated to be about 1300 TWh/year, with a technical potential of 540 TWh/y. Of these only 415 TWh/year are believed to be economically feasible. Of this potential, approximately 330 TWh/year is being utilized presently. Future developments in Europe will be in East countries, because several potential sites exist. However, little evolution is expected between before 2010. The first objective of the European Commission’s White Paper, set for 2003, was not reached (12,500 MW of new capacities production required). The sector’s growth rate remained too weak for that. The economical and technical potential of large dams is already used, or unavailable because of environmental constraints.

There are large small-size hydraulic resources in the European Union. The estimated additional potential capacity of nearly 6,000 MW and only about 65% of this potential is developed. An increase of 4,500 MW for small-size plants is realistic, with a favorable legislation. Concerning 2010 objectives, European small-size hydraulic capacity should be around 12,000 MW if the average annual growth rate of the last four years goes on. Nevertheless, this figure is going to be below the target of the European Commission’s White Paper. It should be underlined that this figure does not take into account the new member countries integrated on May 1 2004, which means that a lot can be done in this area. The total capacity in service of small-size dams, at the end of 2003, for the 15 members, was estimated at 10,734 MW and a lot of small plants are out-of-service, because of a lack of incentive for costs of maintenance. However, their repair needs only little investments, especially for isolated and rural installations. Nevertheless, European countries are leaders on the worldwide small-size hydraulic market.

1.2 General issues on [hydropower] technologies

The IEA has given a good list of some of the characteristics of hydropower [3]:

- There is no fuel cost associated with hydropower, and it is a renewable resource.
- Resources are widely spread and abundant in places.
- It is a proven and well advanced technology, the generation system is well adapted to the power source.
- The technological solutions are characterized by long life-times and low operating costs, and is the only renewable resource not relying on subsidies.
- The fast response times means that hydropower is likely the single best regulating source providing grid stability.

A hydropower facility is a highly efficient producer of electric power. It is highly flexible, and energy not used is effectively stored in potential energy of the water in reservoirs along rivers. Storage by means of water reservoirs is the only mean we have today to store large amounts of energy.

A typical hydropower plant includes a dam, reservoir, penstocks (pipes), a powerhouse and an electrical power substation. The dam stores water and creates the head; penstocks carry water from the reservoir to turbines inside the powerhouse; the water rotates the turbines, which drive generators that produce electricity. The electricity is then transmitted to a substation where transformers increase voltage to allow transmission to homes, businesses and factories.

Depending on the site specifications two types of turbines exist, reaction and action turbines. Action turbines convert the pressure to a water jet that impinges on the impeller to produce mechanical torque, this is mainly used for high head sites. For lower heads the reaction turbine is used, the impeller is contained in a encasing and the pressure energy of the water is extracted by the turbine. Turbines have a large span of operating flows (and thereby power output), compared to the design flow. Typically, the efficiency of the whole station, from the potential energy in the water to electric energy output, is well above 80%, and in some cases can be as high as 95%. Depending on what type of turbine used, the efficiency can be nearly flat for a wide range of flows, or power output, this again makes it a useful technology to use to balance the grid. The produced power does oscillate marginally, mainly due to oscillations in the waterways.

The size of the units has grown with time. Larger units usually show better economy but, on the down-side, when a large unit fail, all generating capacity can be lost. Today, turbines are manufactured from a few kW up to 800 MW. Instead of increasing the upper limit the approach is to install more turbines. The shear weight of the rotating mass sets another limit. In a large hydropower station the rotating mass can exceed thousands of metric tons. The larger the rated output, the heavier the rotating mass will be. Sometimes extra weight is also added to provide stability for the grid, and reduce the danger of over speeding the turbine.

1.2.1 Peculiarities

Hydropower offers advantages over many other energy sources but faces unique environmental challenges. Hydropower is producing electricity on demand. Other benefits may include water supply and flood control.
The fact that the stored water is easily accessible means that hydropower stations have very short starting times, from zero to rated power takes only minutes, even for the largest units. There are a number of factors affecting the time it takes to regulate the power. In the grid, it is desirable to have a substantial amount of rotating energy stored, this contributes to a stable grid. Thus, generators are built with large moments of inertia to provide grid stability. However, in order to regulate a unit quickly a small moment of inertia is needed so the unit can accelerate quickly. Therefore, a compromise has to be found. Further, The waterways around a station also limits the regulation, in order to avoid surges, and to large forces on hydraulic systems regulation times should be kept as long as they can. Despite these limitations, hydropower stations are easily regulated. They can go from zero to rated power in just minutes. For a hydropower station, there is no such thing as a cold-start. When the station is producing power to the grid regulation of the power is very easy, it is governed by the flow through the turbine. And turbines operate over a very large span of power, although, depending on the type of turbine, the efficiency varies to a certain degree. Due to the versatility, in the Nordic grid for instance, hydropower has gone from providing base load power to be used to maintain frequency stability. Without this important frequency, and balance, regulation (provided by hydropower, or pumped hydropower in many places) it would be impossible to introduce other renewable power sources that fluctuates strongly in time into the grid, e.g. wind power. The electricity production is optimized for power and not quantity. The produced kWh is of high quality. Hydraulic energy is often used to store electricity. For example, in France, the installed capacity is about 27 GW (22 % of all electric plants) but the hydraulic production represents only 11.4% of total electric production in 2003. Many countries depend on pumped storage hydropower to maintain the power balance and grid stability. Therefore the importance of pumped storage in the European Union cannot be stressed enough. Large scale hydropower make use of

synchronous generators which can produce reactive power needed to sustain the grid voltage.

Due to the fact that hydropower is used as regulating capacity means that it is utilized to a lesser degree than possible. Dams are built to make it possible to use hydropower as regulating capacity. The extreme case would be a pumped storage hydropower plant. It is a net consumer of electricity (load factor less than zero) with reservoirs and is still very important for grid stability.

Depending on water management, and installed capacity, a station can be used as much as 80% of the total hours during a year. But, since hydropower is used to provide peak power, and balance supply and demand, the utilization time is usually much lower. Due to this the value of having hydropower in the generation mix cannot be overstated.

Among the disadvantages is that it is a renewable energy resource heavily dependent on precipitation. Therefore, the future climate heavily affects the output from hydropower. It is generally believed that the Mediterranean countries face a decrease in annual rainfall which would limit the future power supply from hydropower in those areas. However, the European grid is becoming more interconnected so that a decrease in one area can be covered by an increase in another.

1.2.2 Environmental aspects

Hydropower is a renewable resource that is easily regulated, the fuel is free, nonpolluting, and supplied domestically without any need of transport. However, the structures built to harvest this resource will have an environmental impact. Today, it is the renewable source which contributes the most to electric power production (97% of all renewable electric energy comes from hydropower, making up 19% of the world total electric energy balance [1]), it is likely that this will continue to be the case in the nearest future. Both due to the development taking place at undeveloped hydro sites, and the large cost associated with building a large quantity of new installations for other renewable technologies. On the one hand, developing a hydropower site can take many years due to long approval time, and the large structures needed. On the other hand, the installations have a very long lifetime. Hydropower stations built in the early 1900's are still operational, and it is very hard to reverse the effects from a dam built many years ago. These installations are here to stay.

It is important to differ between pollution and environmental effects, pollution has environmental effects, but all environmental effects does not come from pollution. Hydropower does not pollute since it does not produce waste or any gas emissions. However, hydropower has an environmental impact that will be discussed below. It has been estimated that the hydroelectric production of 1997 reduced the GHG emissions in the atmosphere with an amount comparable to all cars on the planet.

The environmental impact of a hydropower installation touches on a number of issues. First is the question whether a storage space is required, then a dam has to be constructed, or if it is a run-of-river station requiring no dam but without regulation capacity. If a dam is constructed large amounts of material is needed, as well as removing material from other places might become necessary. The dam itself will hinder the migration pattern of fishes, and other organisms having their habitat in the river. The fish-migration problem is sometimes effectively solved with fish ladders, which works well in some locations, and not at all in other. The impact on the fish population can be solved with letting out farmed fish. The change in flow also affect the transport of material which can have large consequences for river deltas. Usually construction of dams are multipurposed. In addition to generating electricity, dams and reservoirs provide flood control, water supply, irrigation, transportation, recreation and refuges for fish and birds. As well as employment opportunities at the installations [4].

The environmental effects of large dams is heavily debated. The main argument is about how much greenhouse gases (GHGs) that are released into the atmosphere from organic material flushed into the dam, or left when the region was submerged. According to a report from the World Commission on Dams [5], “all large dams and natural lakes in the boreal and tropical regions that have been measured emit greenhouse gases ... some values for gross emissions are extremely low, and may be ten times less than the thermal option. Yet in some cases the gross emissions can be considerable, and possibly greater than the thermal alternatives”. The amount of GHGs released from a dam can be sharply reduced by deforestation and clearing before submerging vast land areas. The European Union coordinated action IPPC is also studying the issue, and indicates less severe effects than previously assumed.

Building the dam itself require large volumes of material, and there is always the possibility of dam-rupture, with the environmental and social issues arising. An investigation on Swedish dams showed the need for material during construction (not taking into account the material moved). Depending on site different types of dams are constructed. If the station is underground a large amount of material might surface when excavating the tunnels and infrastructure needed in connection to the station. For the two most common types of dams in Sweden the material used are summarized in the table below, for a selection of 50 of the larger dams [6].

	Rockfill (22 dams)	***Earthfill (28 dams)***
Average [m^3/MW]	5440	11660
Maximum [m^3/MW]	22270	83330
Minimum [m^3/MW]	280	670

The spread in the values are explained by the specific site conditions.

A life cycle analysis of the emissions from hydropower was done in Sweden by two of the largest power companies (Vattenfall and Sydkraft, now EON), and the result is summarized in the table. Note that these figures apply to Swedish conditions, where the water temperatures are lower than for many European countries [7].

Category	***Construction Phase***	***Operational Phase***	***Total***
To air [kg/GWh]			
- NO_x	4.8-7.5	0.13-0.72	5.1-8.1
- SO_2	1.0-1.6	0.06-0.29	1.08-1.72
- CO	2.8-5.1	0.07-6.34	2.9-7.1
- CO_2	474-724, 4800	56-180	576-787, 4980
- CH_4	5.5	0.08	5.58
Particles	0.67	0.17	0.84
To water [g/GWh]			
- N	1.1-2.3, 36	0.15-0.4, 12	1.3-2.6, 66
- P	0.18	0.06	0.24
- Oil	2.2-3.8, 38	159-830, 14	162-832, 52
Waste, [tonnes/GWh]	1.7-27.2	2.3	1.7-27.2

Sometimes in this table two quite distinct values appear, they refer to the two different companies and the respective way they have used to estimate the emissions, and most important to the types of plants operated by the respective companies. Other recent figures [8] for the emissions of CO_2 (from cradle to grave) report estimates that between 100-4000 kg CO_2/GWh depending on the type of plant; smallest for run-of-river plants, and largest for plants with large seasonal storage.

Regarding human lives building large structure can carry work accidents and emitting gaseous emissions can have a detrimental effect on lives. Statistics from 30 years of building and operating hydroelectric power plants showed that hydropower scored the highest number of deaths during construction and operation, mainly due to the fact that large construction projects has unfortunate work accidents. In the operational phase, many hydropower stations are unmanned and therefore extremely safe. Further, regarding the operational phase a report from ExternE [9] concerning the external costs of energy generation (external meaning the indirect cost paid by society during the lifetime of the power plant from emissions) hydropower has the least impact. These low figures means that the number of deaths caused by emissions from hydro is the lowest of all.

	Coal	***Oil***	***Gas***	***Hydro***	***Nuclear***
Historical Deaths/TWh	0.04	0.04	0.04	0.1	$2*10^{-3}$
ExternE Deaths/TWh	25	35	4	<1	<1

One has to realize that if a large dam ruptures, the consequences can be catastrophic for dams situated in densely populated areas. On the four failures in Europe since 1980, three of them were not deadly. In France, this type of accident killed 540 people. But, due to a large research effort, improvement of security since the last important sinister in 1959 (423 victims at Malpasset) has improved the situation quite a lot.

Due to automation, hydropower stations can be left unmanned reducing the risk of work-related accidents further.

Due to the construction of large dams, hydropower has a large footprint. However, compared to coal (where mining can use large areas) hydropower uses only about twice the amount of land area 0.00035 m^2/kWh [7]. When the actual power produced during a year was taken into account.

When considering a source of energy, it is essential to take the amount of energy required to build the necessary installations into account. To this end, the so-called life-cycle energy payback ratio has been defined, which indicates how many times the amount of energy consumed can be recovered in the course of the operational lifetime of a plant. Hydropower is doing extremely well when looked at from this angle, also compared to other renewable sources of energy. Hydropower lies in the range 100-200 times the required energy during the lifetime of the plant, compared to windpower which produces around 50 times the energy needed in construction [10].

1.3 Description of [hydropower] technologies

Electricity generation from hydropower has been around for more than a century and has to be considered as a mature technology. The technological system is well adapted to the nature of the source giving a long lifetime of a generating unit. Hydropower utilizes the potential energy stored in water when the water passes through a turbine.

In economical terms hydroelectric is characterized by a major investment cost (especially when a dam is constructed), a low operating cost due to a high level of automation, high taxation which tends to be on the rise, and no fuel cost. If one also takes into account the longevity of a plant it is a economically very competitive generating technology [11,12]. A recent compiled list in USA [13] states the cost associated with the construction, and operation, of a plant, and gives the following numbers.

Capital investment cost	1400-1900 € /kW
Operational cost	0.33 c€ /kWh
Maintenance cost	0.25 c€ /kWh
Total cost	2.0 c€ /kWh

Based on a 50+ year lifetime, a $/€ rate of 0.836[1], and an average unit size of 31 MW. When studying these figures, one has to bear in mind that these costs are subject to the taxation in the U.S.A., and not directly applicable to European conditions.

In 1997 an European cost-analysis was made [14] with an assumed discount rate of 5% the result is summarized in the table below

c€/kWh	***Investment***	***Generation***	***Total cost***
Run-of-river	2.26	0.26	2.52
Pondage	1.43	0.31	1.74
Seasonal	2.49	0.51	2.77
Conventional stations	1.97	0.34	2.31

For well maintained stations with long life-times indications are that the figures above are slightly overestimated.

Operation and maintenance costs for hydro-electricity plants are considerably lower than for thermal electricity generating plants. There are few unscheduled breakdowns because their mechanical design is relatively simple, and no heat is generated during operations.

Economical and quickly started, this energy is greatly used during peaks, and permits to avoid expensive start of additional thermal plants and thus to save nuclear or fossil fuels. In terms of employment, European hydraulic industry represents about 10,000 jobs, for a turnover of 400 millions Euro [16].

The investment cost can also include added costs due to relocation of people living in the submerged area. A hydroelectric project is a long term undertaking, and therefore it is hard to find figures, or estimates for the cost of decommissioning stations.

1.3.1 [Large scale hydropower]

The investment cost per kW installed power becomes smaller as the unit size increase. Today, the largest size turbines installed in the world are rated 800 MW. There are, in principle, no physical limitations on how large units can be made, only technical. But instead of increasing the size one adds more units. The technology used is adapted to site conditions, e.g. For large head stations action turbines are used, but for lower heads reaction turbines requiring enclosure are used. The station itself can be an underground station, or situated above ground.

1.3.2 [Small scale hydropower]

Small scale hydropower is, by the EU, defined as stations with a power output of up to 10 MW, but as stated before, this definition is different in different countries depending on the conditions. Small scale stations are usually built as run-of-river

1 Exchange rate as of October 24, 2005

stations meaning that they are using the water as it reaches the station. Technological solutions for small scale stations tend to be simpler and components standardized.
The investment costs are usually higher for small scale installations. One report from 2003 [17] gives these figures

Capital investment cost	900-4000 € /kW
Generation cost	0.25-12.50 c€ /kWh

The large span depends on the site conditions.

Compared to large scale stations, the small scale hydropower are usually built using simpler technology, with less regulation capability, but the overall principle is the same. For instance one might use a propeller turbine which has its peak efficiency in a very narrow range of flows. To reduce costs asynchronous generators are usually used together with a gearbox to reduce the size of the generator. Most technical problems in small scale plants are with bearings and gearboxes.

It is generally easier to get the required permits to develop a small scale site compared to a large scale station.

1.3.3 Future [hydropower] Technologies.

When old stations are refurbished hydraulic oil control systems can be replaced, but this does not contribute to a higher efficiency only to the degree of control and safety of the station itself. If we want to increase the efficiency we can address the hydraulic losses associated with the rushing water in the waterways, or the electrical system where losses occur. Today, when existing stations are refurbished, the main improvement comes, usually, from an increased turbine efficiency by exchanging the turbine runner. The waterways can also be improved by streamlining stay vanes and wicket gates. There are also possibilities to increase the efficiency of the electrical system by installation of a high voltage generator.

In places where hydropower is well established it is likely that any extra utilization of unregulated rivers has to take into account all negative aspects mentioned above.
There are, at present, a number of emerging technologies being tested to extract energy from freely floating water, such as currents and tides. They include wind power-like installations under water. This type of power outtake has the advantage of reducing the need for large dams to be constructed. However, this also means that they cannot be used as storage of energy, but they can be used as energy producer, not as balance producers.

1.4 Present [hydropower] Market

Generating electricity using hydropower is a very competitive economical alternative. Especially when the stations have been depreciated during a number of years. Although small scale hydropower is sometimes appraised as the environmentally friendly alternative, it is questionable if it can contribute a substantial amount of energy. As an example, in Sweden there are around 1200 small scale hydropower stations (less than 1.5 MW) contributing around 1.5 Twh/year [7], which is about the same amount of energy produced in one of the biggest stations in Sweden. Thus, one has to compare the environmental impact of one very large station with 1200 small ones. The investment cost per kW for small scale hydropower is generally larger than for large scale. On the other hand it is a local production adding providing opportunities of employment and an contribution nonetheless.

Because the large expansion in installations was made after the 60's nearly 70% of today’s installations are more than 40 years old in Europe. Thus, large investments will have to be made in the nearest future including overhaul or renovation operations for already existing sites. This could create substantial activity among the suppliers. In Sweden, the owners of the Hydropower stations has recognized the need to support research and education to supply competence since many of the people that helped out with the installations in the 60's and 70's are now nearing retirement. Another issue is that, due to the slow investment in Europe, the suppliers for large scale systems (turbine, generator, subsidiary systems) are limited to only a few. For smaller system there are a larger number of suppliers.

1.5 Future development

Due to the fact that the energy in the water is so effectively converted into electrical energy little advances can be anticipated in the design of the technology itself. However refurbishing old plants can add extra energy by an increase in the total efficiency. Studies have shown that replacing old inefficient turbines with new efficient ones can add up to a few percent in the total efficiency. Other improvements possible is to upgrade the water ways in connection with the turbine and thereby reduce the losses. Still more can be gained by installing more efficient generators and electrical equipment. The largest gain usually comes from replacing the turbine runner. It is likely that further development of hydropower has to consider the environmental aspects, such as fish-friendly turbines, replacing high pressure hydraulic oil for control systems with other fluids. Tests made in the USA on fish-friendly turbines indicate a 83-93% survival rate while still maintaining more than 90% efficiency for the runner, although survival rates of larger than 98% were indicated [18].

The European potential for hydropower is reasonably well developed, but there are possibilities for additional generation to be added. However, due to environmental concerns it might be difficult to motivate building the large dams needed for a large scale expansion. Then, there might be an opportunity to use unconventional ways to extract the energy from the freely floating water (see section 3.3.9, for unconventional ways), the disadvantage is that one looses the regulation possibility. It is also believed that small scale hydro can be continued to be developed in many European countries. However, as seen it might not contribute a really substantial amount of energy.

Due to the high efficiency, and economically favorable conditions, it is unlikely that much effort will be placed on developing cheaper new technology. The market is open for competition and is very mature. So the technical solutions we have today are most likely what we will still have the next decades in Europe.

1.6 Conclusion

Hydroelectricity is the most environmentally benign mean to produce electricity which produces a substantial amount of energy, as well as adding real benefits to the grid. This is why it has been extensively developed in Europe in the past. In France, for example, 56% of the electricity was produced from Hydropower in 1960. Small hydraulic should be given incentives to be further developed, and old out-of-service stations refurbished. The main problem to do that is the social acceptance of the energy resource which in fact has only very little impact on the environment. There still exist a large potential for expanding hydropower installations with about 4'500 MW for small scale hydro. In terms of energy the total (small and large scale) potential available is about 80 Twh. Incentives might be needed to boost the development of undeveloped sites, to reach the goal of the white paper.

The investment cost is large (1400-1900 € /kW) but the lifetime is long, and the running costs are low (around 0.5 c€ /kWh) because the fuel is free. The technology is mature and it is unlikely that the installation and operational costs will decrease much as a high level of optimization is already reached. Hydropower plays an important role today and will continue to do so where the conditions exist. Hydropower plays a really important part in a well designed generation mix.

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