The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Back to Basics: Direct Hydropower

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This is a final guest post of Kris de Decker, founder and writer at Low-tech Magazine, an internet publication highlighting the need for elegant yet simple sustainable energy technologies. We published a number of most interesting in-depth energy articles before from Kris about a-typical energy topics including 1) Endless Rope Drives, 2) Small urban wind turbine performance, 3) Heating and Cooling cities without fossil fuels, 4) Fossil Fuel Use in pre-industrial times, 5) solar powered factories for industrial production, 6) Trolley Canal Boats, and 7) The extensive history of windmills. Kris has been sad to hear that The Oil Drum will end its journey, and provides his final contribution on hydropower as a mechanical form of energy, as opposed to hydro-power as a conversion from kinetic to electrical energy, which shapes our conception today when discussing this energy source.

All hydropower plants today produce electricity. Transforming energy to electricity seems to be the only way to harness water power, but it is not. For almost two thousand years, water wheels powered machines directly via mechanical transmission.

Some small direct hydro powered systems in South America present a strong case for combining the use of modern materials with old fashioned methods of water power mechanization.

The higher efficiency of this approach means that less water is needed to produce a given amount of energy. This lowers the cost of hydropower and enables power to be produced by the use of very small streams.

Picture: Direct Hydro Power Coffee Depulper. Picture: Brian W. Raichle

Throughout the course of history, the efficiency of water powered prime movers has steadily increased. Wooden water wheels, which appeared more than 2,000 years ago, converted a relatively small amount of water energy into mechanical power: The efficiency was 5 to 15% for an horizontal water wheel, 20 to 30% for a vertical undershot water wheel, and 50 to 60% for a vertical overshot water wheel. [1]

Iron water wheels, which appeared in the late 18th century, had improved the efficiency rating of the vertical overshot wheel to 65 to 85%. [1] Water turbines, which were developed in the 19th century, and which are the water-powered prime movers that we still use today, generally convert over 85% of the kinetic energy inherent to the water source into mechanical power at the shaft of the turbine. [2] Water turbines are ten to twenty times more compact than water wheels for the same power output, an advantage that led to much cheaper and much more powerful prime movers. Turbines are more widely applicable than water wheels, because water wheels could not make efficient use of any head of water (the vertical distance travelled by the water) much greater than their own diameter. [1]

Why Modern Hydro Power is Less Efficient

In spite of these significant improvements, hydropower installations today are actually *less* efficient than those from earlier centuries. The culprit is electricity. Not long after the introduction of the water turbine, another change occured: Instead of using water-powered prime movers to run machinery *directly* (as had been the case for centuries), water turbines were (and still are) used to generate electricity. This modern approach has introduced an energy deficit that has nullified any progress behind hydropower design efficiency.

Direct Hydro Power Coffee Depulper. Picture: Brian W. Raichle

In a modern hydropower installation, a water turbine converts the energy in the moving water into rotational energy at its shaft, which is then converted into electrical energy by the generator that is coupled to the turbine. Next, the electrical energy is converted back into rotational energy by the electric motor of the machine that is being powered. Every energy conversion introduces energy loss. This loss of energy occurs due to friction, which is observable as heat, vibration and noise. Friction occurs at all levels of electrical transmission: In the turbine, the generator, and the motor. Additional components such as batteries, drive systems and inverters can further increase efficiency losses.

It is possible to calculate the efficiency rating for each modern hydropower unit by measuring the difference between turbine input and electric generator output. A home-sized hydropower plant generating AC electric power has a "water-to-wire" energy transfer of at best 60 to 70 percent. [3] Smaller DC electric systems, which require inverters and generally have battery banks, have lower efficiencies of 40 to 60 percent. [3]

Energy loss in the electric motors of the devices being powered is not included but should also be considered ("water-to-motor" efficiency). The efficacy of an electric motor can vary wildly - from less than 60% for small motors to more than 95% for large motors. On average, a hydro-electric power installation only converts about half of the energy available in water into useful work.

This means that a small, modern hydropower plant has a similar efficiency rating to a centuries old configuration using a wooden vertical overshot water wheel (50-60%), and that this modern counterpart is considerably *less* efficient than the iron water wheels of the 18th century (65-85%). In an old fashioned hydropower installation, there was only one conversion of energy; A water wheel converted the energy inherent to the water source into rotational energy at its shaft. The same shaft also moved the machinery, so that the only source of significant energy loss occured in the water wheel itself. [4]

Direct Hydro Power Coffee Depulper. Picture: Brian W. Raichle

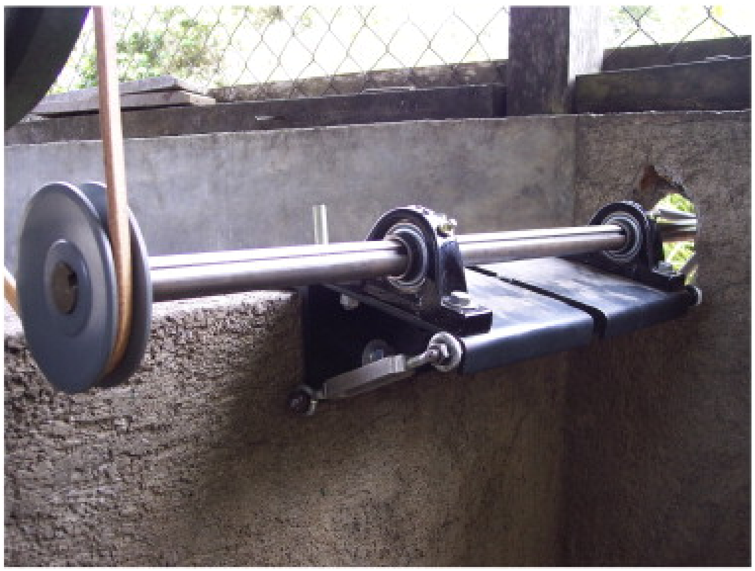
Note that this is not the total efficiency of the hydropower installation: friction also occurs in the pipeline that feeds the water to the turbine. Most small hydropower systems don't use dams. Instead, they divert a fraction of the water of a stream downhill through a pipe. The energy losses in the pipeline are the same for hydroelectric and direct hydropower installations. Therefore, for the purposes of our comparison, these power losses can be overlooked.

Why Direct Hydropower Makes Sense

There is one possible hydropower configuration in particular that deserves considerable attention: a water turbine directly powering machinery, without the intermediate step of generating electricity. Depending on the type of turbine used in such a system, the value that corresponds to the "water-to-motor" efficiency is roughly 80 to 95%. The implementation of this form of direct hydropower doubles the effectiveness of a small scale electric hydropower installation. [4]

The higher efficiency of direct hydropower brings important advantages. If the intermediate step of generating electricity is bypassed, considerably more power can be gathered and utilized from a given head (the vertical distance travelled by the water) and water flow rate (the amount of water that runs down a stream). This advantage can be used to increase the energy production of an existing water power site. It also means that more potential water power sites become available, and that relatively small streams and rivers can be shared by several hydropower units.

Because of its higher efficiency a direct hydropower system is also cheaper than a hydroelectric power system. Less water is needed to produce a given amount of power, which means that all components of the installation are reduced in size, cost, and other resources. For instance, less civil engineering is required. Water can be carried to the turbine by low cost, low pressure, easily transportable, flexible, plastic tubes that are small in diameter as opposed to the rigid, large diameter penstocks common to electric hydropower plants. The flexible connections between the pressure pipe and turbine also simplify installation.



Picture: Direct Hydro Power Coffee Depulper. Source: Brian W. Raichle

Last but not least, the higher efficiency of direct hydropower limits the ecological impact of a water power site. Maintaining enough water in the power source for aquatic life to thrive is a cornerstone of environmentally sound microhydropower production. This type of ecological sustainability is easier to achieve with direct hydropower because less water is required.

Old-School Approach, Modern Materials

Many NGO's are introducing small hydropower systems in the developing world. Almost all of them are aimed at the production of electricity. However, there are a few exceptions to this standard practice. In 2007, a team from the Appalachian University in the US designed, built and installed a direct hydropowered coffee depulper in Nicaragua. According to a recent study in *Energy for sustainable development*, it has "performed flawlessly through five harvests". [5]

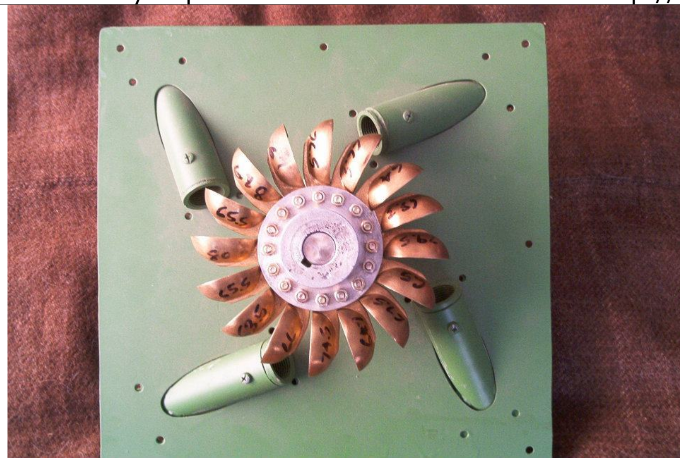
Much of the necessary energy for coffee harvesting and processing is provided by manual labour. One of the most tedious, labour intensive steps of coffee bean processing is depulping. In the past, the depulping process was restricted to a hand cranked machine, and would take all night to complete. Now, with the help of direct hydropower technologies, the depulping can be completed in two or three hours.

The bronze runner of the Watermotor model 150. Picture: Campo Nuevo.

The installation can deliver a maximum of 800 watt mechanical power with a head of 35 m and a water flow of 300 liters per minute. The material costs amounted to just $1900. For comparison, *Practical Action* states that, when using appropriate technologies, a small scale hydroelectric installation costs $1,800 to $6,000 per installed kilowatt. It takes about two kilowatts of mechanical power to produce one kilowatt of electric power, so that direct hydropower is at least twice as economically viable as a hydroelectric operation with the same rate of energy production.

Precise Control

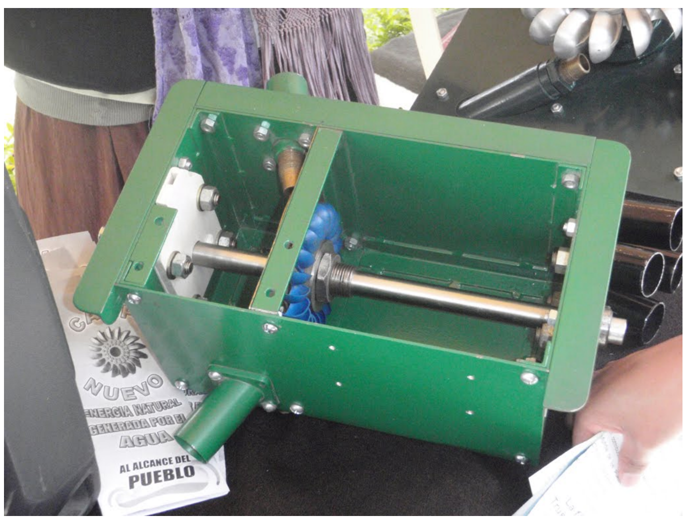
The turbine used by the direct hydropowered coffee depulper is a commercially available *Water Motor model 90* from *Campo Nuevo* in Bolivia. According to the manufacturer, the compact machine (16 x 16 x 32 cm) is "the only modern turbine designed to drive common machines directly with water power". The turbine uses a 9 cm diameter Turgo type runner, which converts water power into mechanical power at 80 to 85% efficiency. It is suited for moderate to high head systems. The larger model 150 has a 15 cm diameter runner and produces about three times as much power.



The Campo Nuevo Watermotor model 150. Picture: Campo Nuevo.

The water motor is as easy to control and adjust as an electric motor. It has a power switch that allows instant on/off control, which makes it practical to directly power machines which must be turned on and off many times during use. The mechanism works by deflection of the water from the runner, so that the force of the flow does not increase the pressure in the penstock.

The power output of the turbine can be precisely adjusted. Like any other turbine of the impulse type, a Turgo runner is driven by high velocity jets of water. A manifold separates the water flow into four smaller tubes, with each stream leading to one of the four jets driving the turbine wheel.



The Campo Nuevo Watermotor in its casing. Picture: Campo Nuevo.

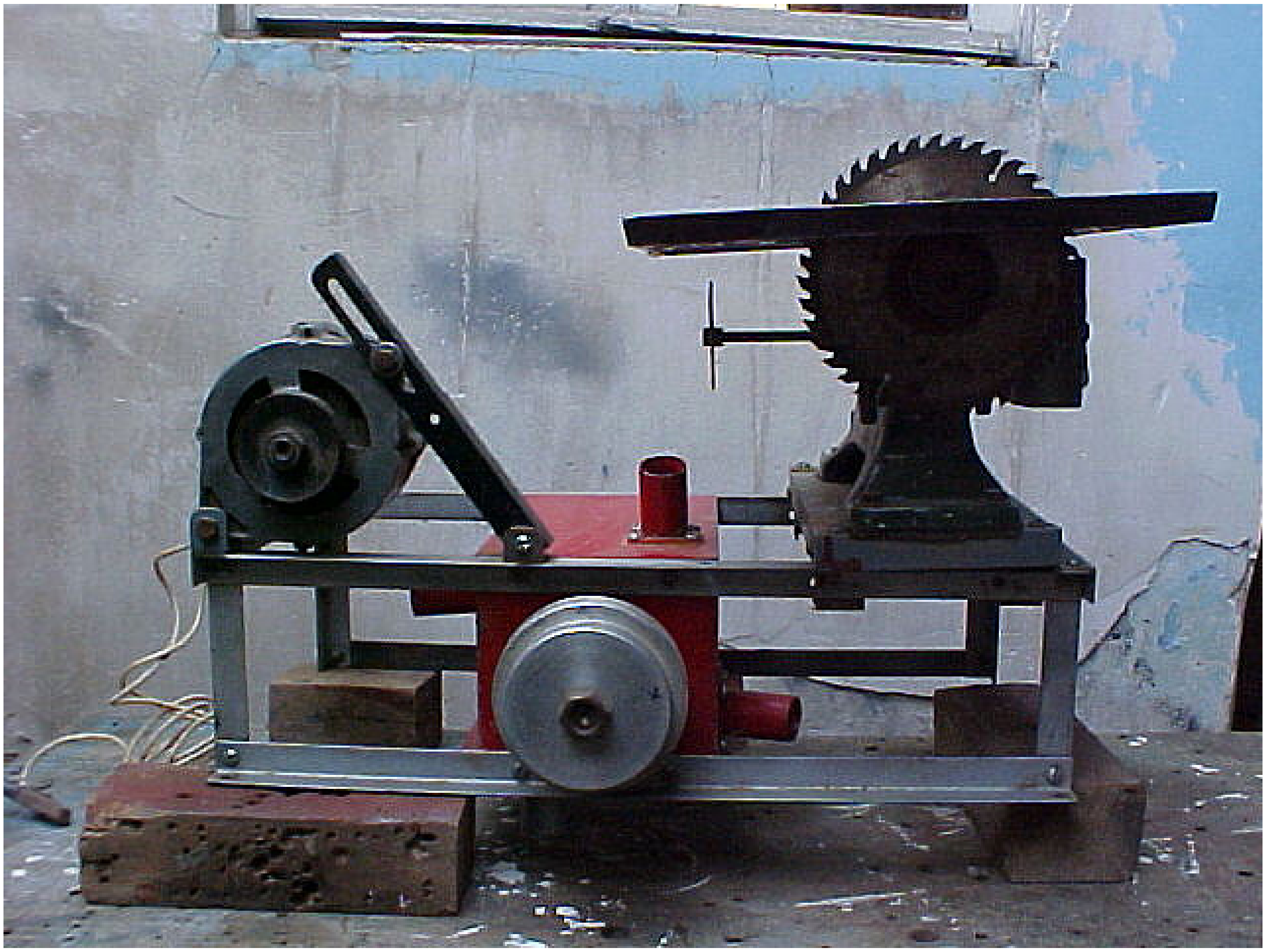
Each of the four nozzles has an individual valve to provide for a range of flows, so that the motor can be run on one to four jets at a time. Furthermore, the jets can be adjusted to various sizes. This mechanism makes it possible to precisely measure and adjust the power output of the motor and cater to seasonal variations in water flow.

Direct Hydropowered Woodworking Unit

At the *Campo Nuevo* demonstration site in the Andes, the water motor runs a large variety of machines, including a small woodworking unit (table saw, grinder, joiner, drill, abrasive disk), a cement mixer, and a grain mill. When mechanical power is not being used by any of these machines (for instance at night),the motor runs a generator which stores electric energy in batteries for lighting and other purposes. The water motor can also operate an air compressor to run air-powered tools. (In principle, it could also run a compressor from a refrigerator). [6]

The water motor on the demonstration site delivers power similar to a 0.75 horse power (560 watt) electric motor at 1,450 rpm using a stream with a vertical fall of 18 m and an average water flow of 310 liters per minute. These conditions are less than ideal for a hydroelectric power site, but for direct hydropower the situation is perfect.

A small storage tank attached to the direct hydropower unit even makes it possible to temporarily run more powerful machines. Since the operation of the table saw requires 500 liters of water per minute (which is often not available), the 6,000 liter storage tank was installed, measuring 2 x 2 x 1.5 m. It allows the table saw to run for 15 minutes continuously. This additional power output adds up over two hours of operating time over the course of a ten hour workday.



A set-up of a water motor running a table saw and generator. Picture: Campo Nuevo.

All machines (including the generator and air compressor) are placed directly on or beside the turbine housing. These tools are attachable to (and driven by) the same belt. The water motor can only operate one machine at a time, since there is no distribution of energy. This works well in a workshop, because many tools and machines are used intermittently.

The same configuration is used for the direct hydropowered coffee depulper in Nicaragua, which was described above. Coffee beans are harvested from December through February, and they must be depulped within 24 hours of picking. This processing constraint means that the depulper is only used at night for a small fraction of the year. Therefore, the direct hydropower installation is often available for other applications (such as running a saw, a drill, an air compressor, or an electric generator). Although the turbine that powers the coffee depulper can provide up to 800 watts of mechanical power, the coffee depulper itself uses only one fourth of that waterpower and one jet to deliver 200 watts for its operation.

Upgrading Medieval Water Mills

Will we see a rebirth of direct hydro power? Maybe, but the fact remains that this form of energy production has never disappeared. In some mountainous regions, there are still water wheels in operation that share similar design with the water mills so extensively used in medieval Europe. The rotating shaft directly drives machinery, most commonly found today as grain mills for flour production.

In remote villages in Nepal, many farmers use all wooden traditional water mills to grind grain. About 25,000 to 30,000 of these are still in operation today. In Nepal, the goal is not to reintroduce direct hydropower, but to make sure that it *stays*. That is why the national NGO Central for Rural Technology Nepal (CRT/N) runs a program to upgrade these mills. The improved water wheels can grind grain more efficiently and have longer lifespans, which allows them to compete better with diesel powered mills.

CRT/N have increased the efficiency of water mills in Nepal by replacing wooden runners with precision-made metal ones. Picture: CRT/N.

Basically, CRT/N upgrades medieval style water wheels to nineteenth-century style water wheels, by replacing key wooden parts such as the shaft and the runner with locally produced precision metal parts. The wooden penstock that delivers water to the mills is replaced by a high density polyethylene pipe which reduces leakage and other avoidable problems.

CRT/N calls its technology the Improved Water Mill (IWM). Estimates suggest that grinding capacity of the upgraded mills has doubled, which corresponds neatly with the efficiency figures we introduced at the beginning of this article. The higher efficiency makes that less water is needed and that the mills can operate for longer periods of the year.

Replacing Diesel Engines

The NGO has upgraded 5,700 water mills from 1990 to 2009. Some of these upgrades (237 to be precise) also involved adapting water mills so that they can run other machines as well, such as oil presses, rice de-huskers, sawing machines, or an electric generator. To achieve this variability, a longer shaft is installed which disconnects the runner from the millstones. Instead of connecting to the millstones, the grinding shaft operates from the long shaft using a belt drive, allowing other machines to be operated by direct hydropower.

With a long-shaft attachment, several machines such as a rice-huller can be run from a mill. [*Picture: CRT/N.*]

While these upgraded water wheels do not achieve the high efficiency of direct hydropower installations using turbines, they are less expensive. Basic upgrades of a water mill cost $350, whilst the option of running multiple machines brings the total cost at $900 to $1,200. Thus, upgrading a traditional water mill is at least two times cheaper than installing a complete new, turbine driven direct hydropower system. In Nepal, improved water mills have even replaced some diesel powered grain mills, because they are less expensive to run and produce better quality flour.

The water mill upgrade project is still [ongoing]. Similar but much smaller projects have been implemented by [IT Power India], also in the Himalayas (70 upgraded mills at a cost of $200 each), and by [SITMo] in the Philippines (as part of a mostly electric hydro scheme).

The best of both worlds

This plea for direct hydro does not imply that we should stop using electricity. Some things cannot be powered by mechanical energy, most importantly lighting and electronic equipment.

Furthermore, many people in the developing world do not have access to electricity at all, forcing them to use unhealthy kerosene lamps instead.

Rather, the examples described above show that it might be interesting to combine both methods. The best results would be obtained by a hydropower installation that produces mechanical power for operating machines, and stores electric power in batteries for lighting and other purposes when mechanical power is not required (for instance at night). Compared to a strictly mechanical system, it would offer important extra benefits. Compared to a merely electric system, it would deliver more power and be much more efficient.

Water motors can also be used if you don't have a mountain stream running next to your house, farm or factory. That's the topic of an upcoming post. Stay tuned and get updates by email, feed, facebook or twitter.

Kris De Decker (edited by Caylen Cole-Hazel)

Notes & Sources

[1] *Stronger than a Hundred Men: A History of the Vertical Water Wheel (Johns Hopkins Studies in the History of Technology)*, Terry S. Reynolds, 1983. See pages 106, 306-307, and 342-349.

[2] The efficiency of a water turbine depends on the type of turbine used. There are many types of turbines available, and each one is aimed at specific combinations of head and water flow. For small-scale hydro applications, a minimum efficiency of 80-85% can be achieved in any situation. Pelton turbines are up to 90% efficient and large turbines can be over 95% efficient.

[3] *Intro to Hydropower*, Home Power Magazine, 2012. Another source is the *Fact Sheet MicroHydro* of Appalachian State University, which gives an average system efficiency of 53% (including energy loss in the pipeline). And a recent study states: "It is common to assume an overall system efficiency of 50–60%. However, in practice actual power output may be as low as 30% of gross input power for very small installations and as high as 70% for larger schemes."

[4] To this should be added the energy loss in the drive train, which is needed to match the rotational speed of the prime mover with that of the machine being powered. This loss has been included in the efficiency results of modern hydro power installations, where a drive system is used to match the rotative speeds of turbine and generator, but not in the results for the old-fashioned installations. The energy loss in the drive train can be quite large, for instance when you would use a slow-turning water wheel to operate an electric generator or a circular sawing machine, which require high rotational speeds and thus elaborate gearing to step up the speed. On the other hand, the energy loss in the drive train can be negligible when a water turbine is used to directly power fast-rotating machinery, because water turbines have much higher rotational velocity than water wheels. This also holds true for water wheels operating machines which do not require high rotational speeds. Turbines operating slow-rotating machines will need gearing to step down the speed. If the connection is made by a single gear, chain or belt, the drive train can be up to 99% efficient.

[5] *Design and Construction of a Direct Hydro Powered Coffee Depulper*, Energy for Sustainable Development 16 (2012) 401-405. Brian W. Raichle, Raymond S. Sinclair, Jeremy C. Ferrell.

[6] *Water Power in the Andes. Yesterday's Solution for Today's Needs*, Ron Davis, 1999

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- The mechanical transmission of power (1): Stangenkunst
- The mechanical transmission of power (2): Jerker line systems
- The mechanical transmission of power (3): Endless rope drives