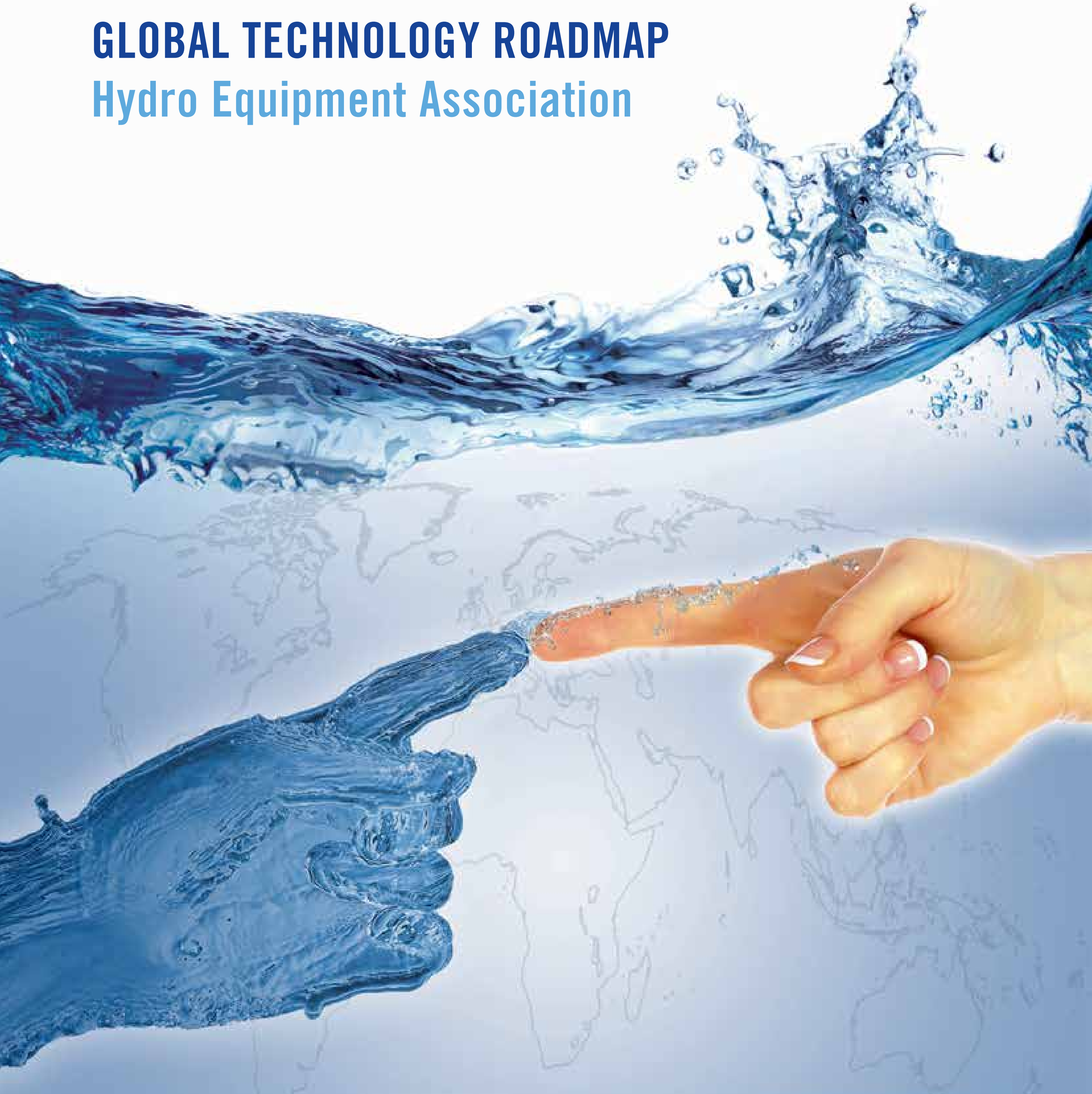
Hydro
Equipment
Association

GLOBAL TECHNOLOGY ROADMAP

Hydro Equipment Association



Introduction

This Global Technology Roadmap sketches out the contribution of the hydro equipment industry to today's and tomorrow's energy challenges. The scope of this document includes the components that convert water flows into electricity; it does not include structure (e.g. dams and conduits).

The primary audience for the Global Technology Roadmap is international financing institutions and policymakers in countries with hydropower potential. NGOs, public and private sector researchers and the general public shall also find it interesting.

MESSAGES TO POLICYMAKERS

The industry operates in a tightly regulated space, shaped increasingly by policies to make energy affordable, secure and green. The Global Technology Roadmap outlines the hydro equipment suppliers' requests to policy makers.

ECONOMIC AND SOCIAL BENEFITS

The Global Technology Roadmap sets out the megatrends in electricity demand and demographics to the middle of the century. It provides evidence of the direct contribution that hydro equipment (in its manufacture, installation and operation) is making to economic and social wellbeing.

TECHNOLOGY

The heart of this Roadmap is a section presenting the merits of hydro equipment technology and the services it provides to the energy system. Technology Outlook sub-headings outline the further developments and research needs to make hydropower even more productive and flexible.

SUSTAINABILITY - A DRIVING FORCE

Sustainability is taken seriously by the hydropower sector. Equipment has been and may further be modified to minimize any negative impacts on eco-systems and maximize any positive ones.

This Hydro Equipment Technology Roadmap was developed by the Hydro Equipment Association (HEA) with contributions from Andritz Hydro, GE and Voith. Unless otherwise indicated any pictures, diagrams or charts are provided by HEA or these organizations.

The Hydro Equipment Association (HEA) was founded in 2001 and represents electro-mechanical equipment suppliers for hydropower globally. Its work is dedicated to advancing sustainable hydropower worldwide by promoting an industry with a long tradition of engineering excellence.

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Foreword

Hydropower is a cost-effective renewable electricity source offering high efficiency and operational flexibility, as well as low operating and generation costs. As of early 2015, around 160 of the world's countries use hydropower technology for power generation, with hydropower plants providing at least 50% of total electricity supply in more than 35 countries as of 2012.

Despite this, there is still large untapped technical potential, particularly in Africa, Latin America and Asia. Half of the world's technical hydropower potential exists in Asia and 20% in Latin America.

However, as the renewables revolution gains momentum worldwide, hydropower looks to become an even more strategic player. In IRENA's roadmap for a doubling of the global share of renewable energy in the energy mix, REmap 2030, world hydro capacity increases by 60% between 2012 and 2030, from 1,000 GW to 1,600 GW, if all the potential presented in the study were implemented worldwide. Pumped hydro more than doubles in the same period, from 150 GW to 325 GW globally.

Small hydropower projects can gain recognition as a very attractive renewable energy development option, providing low-cost electricity to remote communities and to the grid. However, hydropower also provides ancillary services. It offers flexibility when integrating other renewables into the power grid at affordable cost. It can play an important role in the global development of low-carbon energy systems and it offers benefits in relation to flood control, water storage and irrigation.

In order to use local resources at competitive costs and without significant adverse environmental impact, industry knowledge and design experience are essential. For example, increasing production in a sustainable manner means doing so whilst minimizing impacts on ecosystems. Examples of how this challenge can be addressed include adding turbines to unpowered dams and replacing existing turbines with more efficient upgrades.

When fully embracing sustainability, hydropower development can have a positive impact on social, economic and environmental considerations. For example, in Africa the addition of hydropower plants can increase energy access and help to address rapidly expanding energy demand across the continent.

The Global Technology Roadmap of the Hydro Equipment Association is a useful tool to help steer decision makers towards greater appreciation and understanding of hydropower's competitive, dynamic and diverse nature, and the key role that hydropower can play in the global transition to a sustainable energy future.

Adnan Z. Amin
Director-General
International Renewable Energy Agency (IRENA)

Setting the scene

Mature but up-to-date; well proven but innovative; economically competitive and still with huge potential.

This is hydropower as we know it. This is the message we wish to convey to governments and policy makers worldwide to ensure the further deployment of hydropower. Within this Global Technology Roadmap, the Hydropower Equipment Association (HEA) is giving hydropower technology a global voice.

Worldwide electricity systems continue to groan under the pressure to meet the rising hunger for energy. With less than one quarter of the world's technical hydropower potential exploited, and with developing and emerging countries driving its expansion, hydropower has a major role to play with all of its advantageous benefits.

Hydropower is an up-to-date technology. Equipment manufacturers have always been fast and successful in exploiting the capabilities of advanced engineering. Through Fluid Dynamics Modelling we have reached the highest efficiency levels for hydropower, which are outstanding in power generation.

Research & Development efforts continue to fulfil a wider range of demands and enable hydropower equipment to incorporate a diverse range of features. Pumped storage technology is pushing the boundaries to increase flexibility and the service life of turbines. Furthermore, hydropower is the perfect balancing partner to complement the broad range of intermittent renewable energy like wind and solar, which will be required to power tomorrow's electricity system.

Our Global Technology Roadmap sketches the technological trends that the hydropower manufacturing industry is currently focusing on. We offer the best solutions in order to answer growing electricity demands from large cities to the smaller, more remote areas of the world.

Hydropower projects can have many positive impacts on the local environment, and they strive to improve social and economic conditions wherever possible. In certain parts of the world local people have been recruited by equipment manufacturers to work on their hydro training and apprentice schemes. Indeed by 2030, IRENA's reference scenario estimates suggest that hydropower will be the second largest source of employment within the renewables industry.

Sustainability continues to be at the heart of all hydropower development. It is a driver for innovation where environmental considerations are advancing technological developments across the industry. As an active supporter of the Hydropower Sustainability Assessment Protocol, HEA is committed to actively advocating its worldwide application.

Dr Roland Münch
President of the Hydro Equipment Association
Member of the Corporate Board of Management of Voith
Chairman of the Management Board of Voith Hydro

Lac de l'Hongrin (Hongrin-Léman pumped storage plant), Switzerland.

Messages to policymakers

KEY MESSAGES:
- Support the feasible exploitation of untapped potential
- Embrace sustainable hydropower
- Set-up a suitable framework for hydropower
- Facilitate hydropower deployment
- Reward hydropower for the full value of the ancillary services (e.g. flexibility) it brings to the system

SUPPORT THE FEASIBLE EXPLOITATION OF UNTAPPED POTENTIAL

It makes sense to develop hydropower. This renewable and almost greenhouse gas emission free power can provide some of the lowest-cost electricity of any source. It also has the unique added value of providing other services such as water supply, irrigation and flood control. Significant low-cost hydro potential still remains to be exploited in many developing and emerging countries in particular Asia, South America and Africa.

Hydropower is a proven and innovative technology based upon many years of experience and expertise. Hydro equipment manufacturers still continue to push technological developments and respond to current demands for increased flexibility, more frequent load changes and greater availability.

Important barriers to hydropower development need to be overcome. These include:

> Public acceptance
> High initial investment costs
> Long lead times to obtain or renew concessions/environmental authorizations
> Hydropower development can sometimes conflict with water/environmental policies
> Need for planning coherent and simplified administrative procedures which encompass site specific particularities.

EMBRACE SUSTAINABLE HYDROPOWER

The Hydropower Sustainability Assessment Protocol should be used more widely, and more assessments should be published. Governments and international financial institutions are encouraged to follow the recommendations of the World Bank as set out in its paper *'The Hydropower Sustainability Assessment Protocol for use by World Bank clients* [WB 2014]. It encourages its public sector clients to use the Protocol on a voluntary basis and emphasizes the need for full client ownership and a long-term perspective towards continuous improvement.

SET-UP A SUITABLE FRAMEWORK FOR HYDROPOWER

Governments should:

> Make sure that regulatory frameworks in place at the time of the decision to build a hydro project are maintained to allow stability and predictability for the duration of its economic life.
> Avoid long lasting permitting procedures.
> Ensure a level playing-field for all power technologies. From vertically integrated to deregulated, markets should provide a level playing field for all power technologies. More specifically in Europe, the electricity market should be the place where suppliers of electricity are remunerated for their product and services to the grid.
> Internalize the external costs of power generation. The HEA supports carbon pricing to reflect the amount of carbon emitted. This would bring forward not only hydro but all green energy technologies while providing a level-playing field for sustainable development, energy poverty abatement and climate change mitigation.
> Remove inconsistent grid fees. In some countries, the owners of pumped storage plants are charged grid fees both when pumping and turbining. This illogical approach eats into the margins of pumped storage plants operations and makes the technology a less attractive investment. This situation persists in spite of the awareness in many governments that greater PSP investment is necessary.
> Remove barriers to setting up local on-site manufacture.

FACILITATE HYDROPOWER DEPLOYMENT

Public Private Partnerships: an excellent way to finance hydro projects

We support financing models that share the risk and rewards of hydropower development between the public and private sectors.

Public sector involvement in financing keeps loan costs down and can ensure that projects, if necessary, sacrifice some output for the sake of water resource management and other economic or social benefits. This is usually the case if international financial institutions are lending, the IEA notes [IEA 2012]. The private sector, meanwhile, brings its expertise to bear in project management and execution.

Between May and September 2011, India's first private sector large-scale project was built, Karcham Wangtoo, which has four generating units of 250 MW each.

Box 1: Large-scale private sector projects are being built in markets that are deregulating

Examples of projects financed by an international financial institution are Cambambe II (Angola), where the World Bank group's Multilateral Investment Guarantee Agency (MIGA) underwrote around USD 620 million for the project's international lenders. In addition Edéa I (Cameroon) received € 65 million in support from the European Investment Bank.

Provisions to take account of the longevity of hydro projects

Hydro projects, having very high investment costs and low operating costs, need conditions that enable them to spread the repayment of those investment costs over long periods.

It should be easier to access loans with tenures approaching the lifetime of hydro projects. These will be needed to finance the expansion of hydro capacity. IRENA estimates that the 26 countries modelled in its scenario for doubling renewable energy production by 2030 would need to spend USD 11 billion per year on greenfield projects. Additionally, we estimate that the refurbishment rate should be increased from 10 to 30 GW per year to avoid an increase in the average age of the world's hydro fleet.
Long-tenure loans depend on a greater willingness by governments to commit to maintaining the regulatory framework that is in place at the time of the decision to build the hydro project for the duration of its economic life. The framework should be stable, predictable and transparent.

Licensing and tendering rules

Licensing procedures should be streamlined where they concern the upgrade of hydro equipment installed at an existing site. The procedures should be far less burdensome and onerous than for greenfield projects.

Project tendering rules should allow for the fact that in the long time that it can take to develop a project, better technologies might become available than those put forward in the original tender. It should be possible with minimal paperwork and red-tape to swap in these better technologies or cost effective solutions.

Secure local education and capacity building in developing countries

The long-term engagement of local authorities in education and training centres set up with Hydro Equipment manufacturers must be secured, with a particular focus on training people living close to a hydro plant to operate it. This especially applies where operation of such centres is transferred to local or regional institutions after a defined period.

Construction of São Salvador hydropower plant, Brazil.

REWARD HYDROPOWER FOR THE FULL VALUE OF ANCILLARY SERVICES

Electricity grid regulators should:

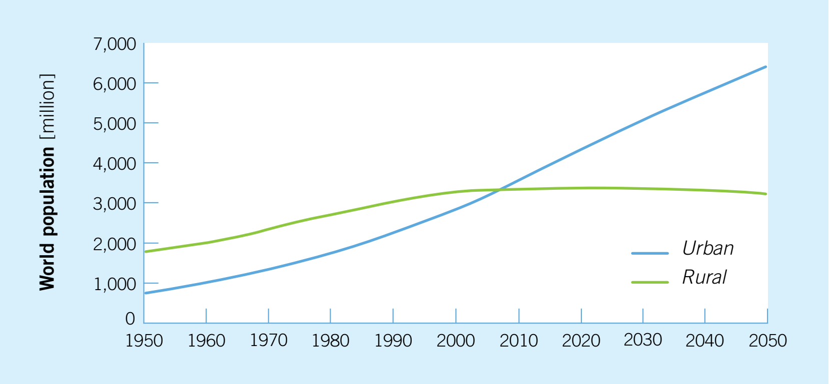
> Ensure that in countries where unbundling has taken place and electricity markets are liberalized, ancillary services get a fair remuneration via market mechanisms. These markets will reward, for example, hydro's flexibility and fast reaction time or its ability to provide voltage control. Remuneration of these services would improve the business case for new hydro investment. Hydro's role in providing ancillary services (including its ability to restart the grid in the case of electricity grid collapse) has often been neglected.

> Impose rules and electricity balancing methods that take account explicitly of network power transfer limits (between control areas and within control areas) as well as storage potentials. Doing so would allow balancing of variable-output generation (typically wind and PV) to be done closer to real time, improving the overall efficiency of the power system.

> Harmonize national balancing markets across the European Union. The structure and rules of today's national balancing markets differ greatly. Greater harmonization of some of these is possible (although unlikely to be possible for all because of different balancing resources being available in each country) and would enable standardized balancing products to be created. This would facilitate the emergence of cross-border trade in balancing power, which lowers the overall system cost by reducing redundancy.

Rising worldwide electricity demand

RISING URBAN POPULATION…



All the net growth in the world's population will be in urban areas, where the Earth's 9.6 billion inhabitants will live in the ratio 2:1 by mid-century [UN 2014].

…DEMANDING HIGHER LIVING STANDARDS

Electricity is an indispensable part of any vision of a productive, busy world. It unlocks opportunities for education, entertainment, comfort and convenience. Of these things, more is never enough.

Towns and cities are pulling populations to them. Living densely multiplies the opportunities for human interaction, which generates wealth. The predictions are of a doubling of per capita GDP by mid-century [EXXON 2014a] and of demand for electricity outstripping the growth in energy demand overall (Figure 1). It will "meet 33% of non-transport energy demand in 2030, up from 28% in 2011" [BP 2013].

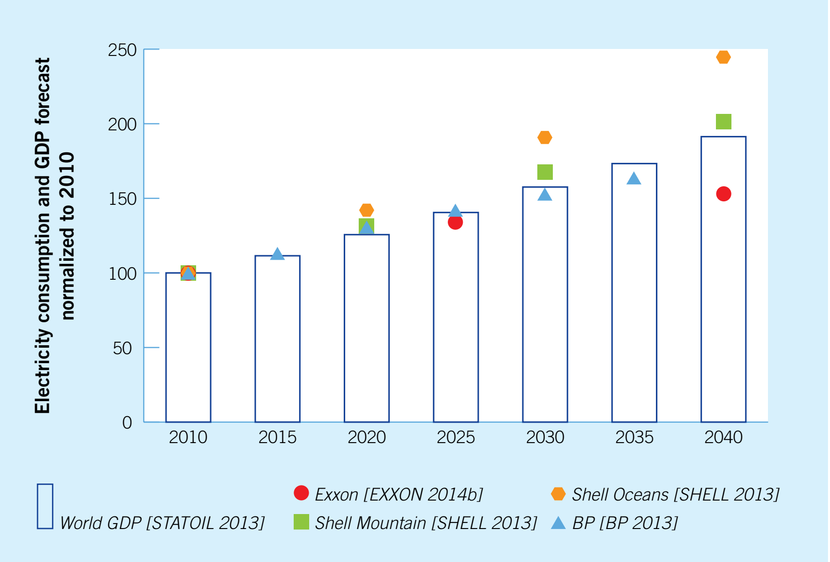


Figure 1: World GDP increases by roughly 2.5 % per year to 2040, accompanied by growth in electricity consumption. The growth in other forms of non-transport final energy is less.

Our electricity system has to cope. It has to supply exactly the power we need affordably, reliably, ecologically and at the time we need it. Intelligently combined renewable energy generation (harnessing hydro, wind, solar, biomass, geothermal or marine resources) can satisfy these requirements. The renewable energy revolution, which has already reshaped energy markets and investments across the globe, is only just starting.

Hydropower – able to meet the demands of billions

Emerging and developing countries building large projects will drive most of the growth in hydroelectricity generation. Through the power that these plants generate, local populations will be lifted from poverty and social and economic development will ensue. Small hydro and mini or micro grids can help to meet the demand of the remotest and poorest people. In industrialized countries refurbishment of plants is a cost effective way to improve the economics of hydroelectricity generation and further enhance safety (Figure 20, page 31).

EXCELLENT RESOURCES REMAIN UNTAPPED

The latest estimates of hydropower's technical potential are, in terms of generation capacity (i.e. excluding pumped storage), around 4,400 GW worldwide, of which 1,100 GW have been installed. Hydroelectricity generation in 2013 was 3,800 TWh, against a technical potential of 15,800 TWh (Figure 2) [IJH 2014]. 'Technical potential' means the amount of hydro output obtainable by full implementation of demonstrated technologies or practices.

In all, a quarter of the world's technical hydropower potential has been exploited. International agencies and oil majors have published scenarios that offer an insight into how much of that potential will be developed and where (Box 2).

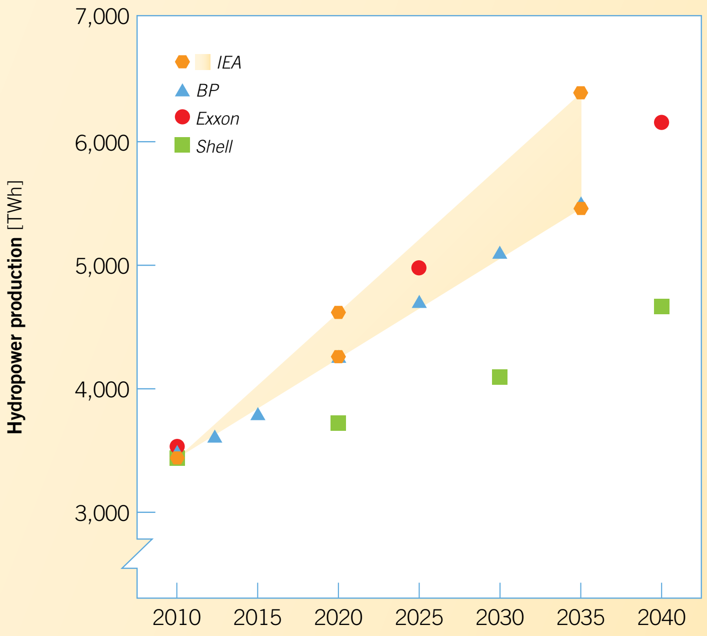
23% of reservoirs worldwide in the range 100 to 1,000 billion m^3 have not been equipped with hydropower generation capability [ICOLD 2007]. They are used exclusively for other purposes (e.g. irrigation, flood control, navigation and urban water supply). These dams all represent potential that may be easy to exploit without or with minimal impact to their primary purpose.

SCENARIOS OF DIFFERENT INTERNATIONAL ENERGY AGENCIES

The IEA's forecasts of hydropower production range from 5,478 to 6,394 TWh globally in 2035 (with production of 3 490 TWh recorded for 2011) [IEA 2013]. The upper end of the projection range is that of the '450 ppm' scenario in which the world adjusts its energy policy to meet a 450 ppm CO_2 concentration by 2050. The increases for 2035 are in the range of 60-80% on current generation.

IRENA initiated work in 2012 towards plotting a path to a doubling of the share of renewable energy in the world's energy consumption by 2030. The scope of its study is 26 countries which are together expected in 2030 to account for three quarters of total final global energy consumption. Under the REMAP 2030 scenario, which achieves the doubling, hydroelectricity production almost doubles between 2010 and 2030. Under a reference scenario, the increase is 70% [IRENA 2014].

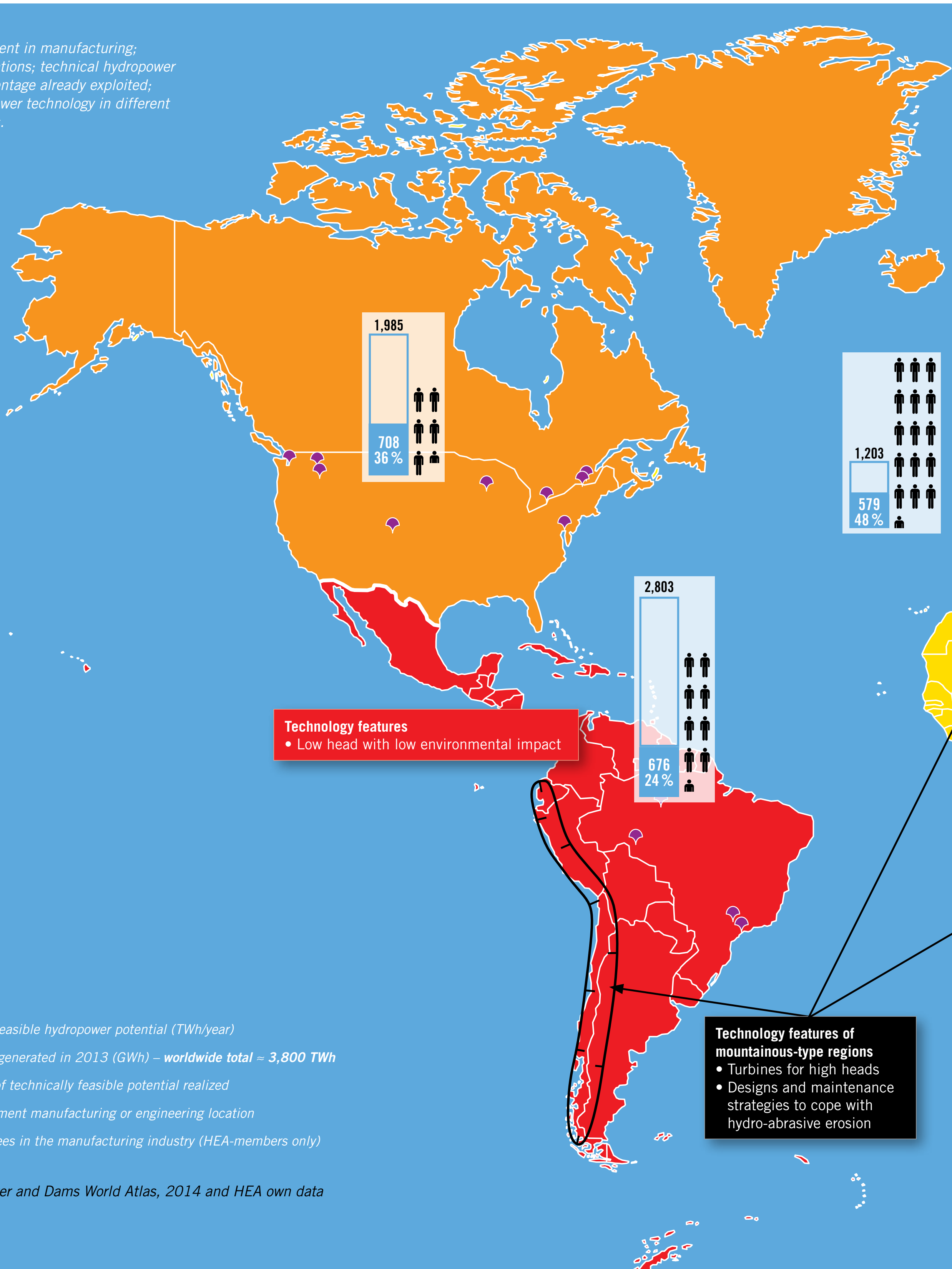
WORLD SCENARIOS



Box 2: The energy agencies IEA and IRENA foresee strong hydro growth, oil companies less so.

HYDROPOWER IN FIGURES

Figure 2: Employment in manufacturing; manufacturing locations; technical hydropower potential and percentage already exploited; features of hydropower technology in different color-coded regions.



Technology features
- Low head with low environmental impact

Technology features of mountainous-type regions
- Turbines for high heads
- Designs and maintenance strategies to cope with hydro-abrasive erosion

■ *Technically feasible hydropower potential (TWh/year)*

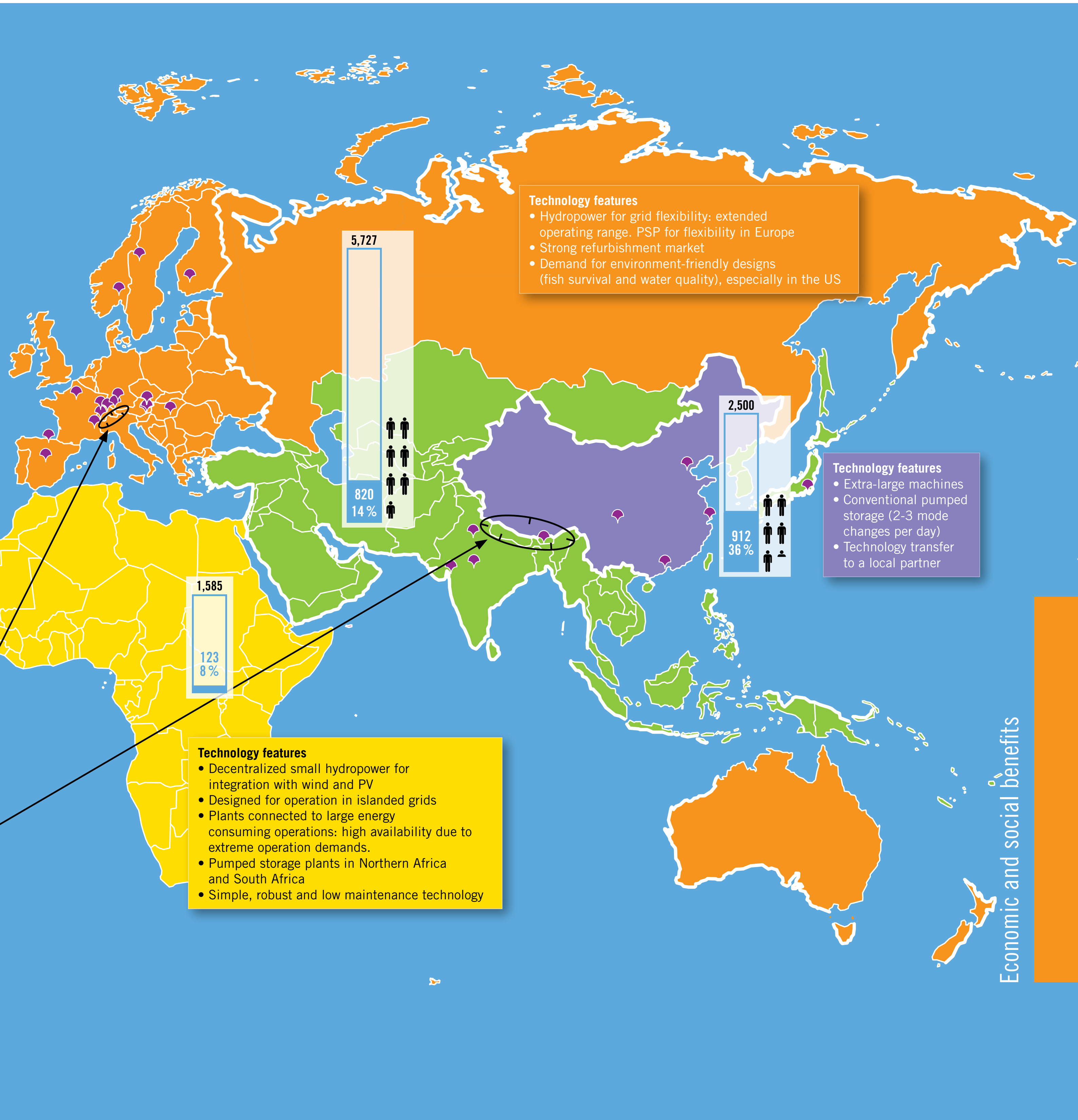
□ *Hydropower generated in 2013 (GWh) – **worldwide total ≈ 3,800 TWh***

% *Percentage of technically feasible potential realized*

◆ *Hydro equipment manufacturing or engineering location*

🯅 *500 employees in the manufacturing industry (HEA-members only)*

Sources: Hydropower and Dams World Atlas, 2014 and HEA own data



Technology features

- Hydropower for grid flexibility: extended operating range. PSP for flexibility in Europe
- Strong refurbishment market
- Demand for environment-friendly designs (fish survival and water quality), especially in the US

Technology features

- Extra-large machines
- Conventional pumped storage (2-3 mode changes per day)
- Technology transfer to a local partner

Technology features

- Decentralized small hydropower for integration with wind and PV
- Designed for operation in islanded grids
- Plants connected to large energy consuming operations: high availability due to extreme operation demands.
- Pumped storage plants in Northern Africa and South Africa
- Simple, robust and low maintenance technology

RESOURCES THAT YIELD LOW COST ELECTRICITY

Where water is available, hydropower can generate electricity at unbeatable costs.

> “Hydropower is already mature and economically competitive; as a result, deployment is projected to proceed steadily even in the absence of ambitious efforts to reduce GHG emissions.”
> – IPCC 2011

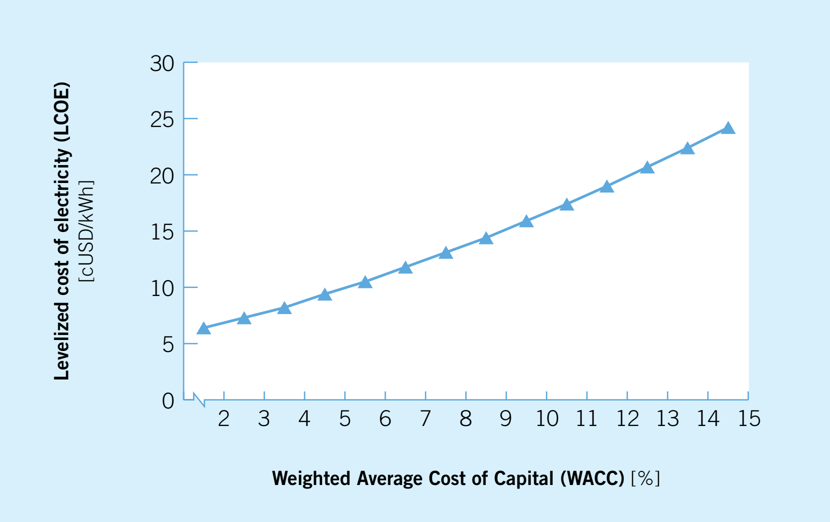


Figure 3: The dependence of LCOE on WACC taking the case of the Adjarala hydro plant on the Benin/Togo border

Estimates of ‘**L**evelized **C**ost **O**f **E**lectricity’ or LCOE are sensitive to the **W**eighted **A**verage **C**ost of **C**apital (also known as WACC or ‘discount rate’) that should be applied to future cashflows. They are less sensitive to the expected lifetime of the plant. A large amount of the capital expenditure in a medium-to-large-scale greenfield project is in civil works (penstock(s), tailrace, surface and/or underground buildings). These constructions have lifetimes in the range 80-150 years. The net present value (NPV) of cashflow more than 80 years into the future is near zero, even at low discount rates. Figure 3 illustrates the sensitivity of LCOE on WACC for one example from Benin/Togo.

The IEA, IRENA and Bloomberg New Energy Finance have all in the last three years published consistent LCOEs for hydro and other technologies using appropriate assumptions about WACCs (Box 3). The LCOE for refurbishments and upgrades ranges from as low as 10 USD/MWh for additional capacity at an existing hydropower project to around 50 USD/MWh for a more expensive upgrade project assuming a 10% cost of capital. The cost-effectiveness of refurbishments is unsurprising, as the cost of hydro equipment makes up only a small proportion of all the costs in the development of a greenfield site (Figure 4).

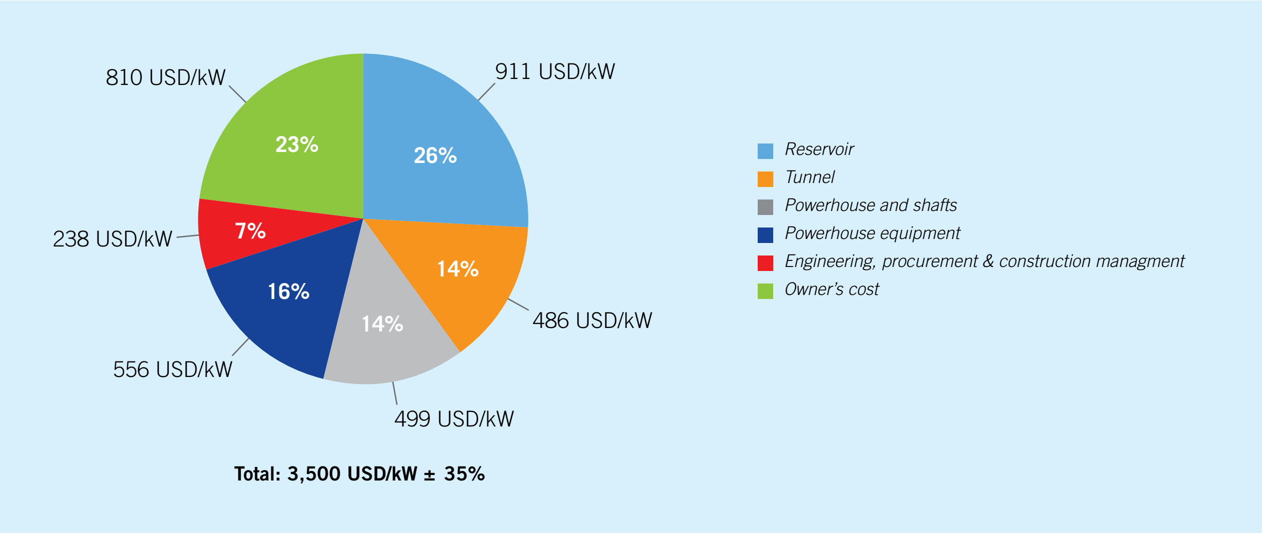
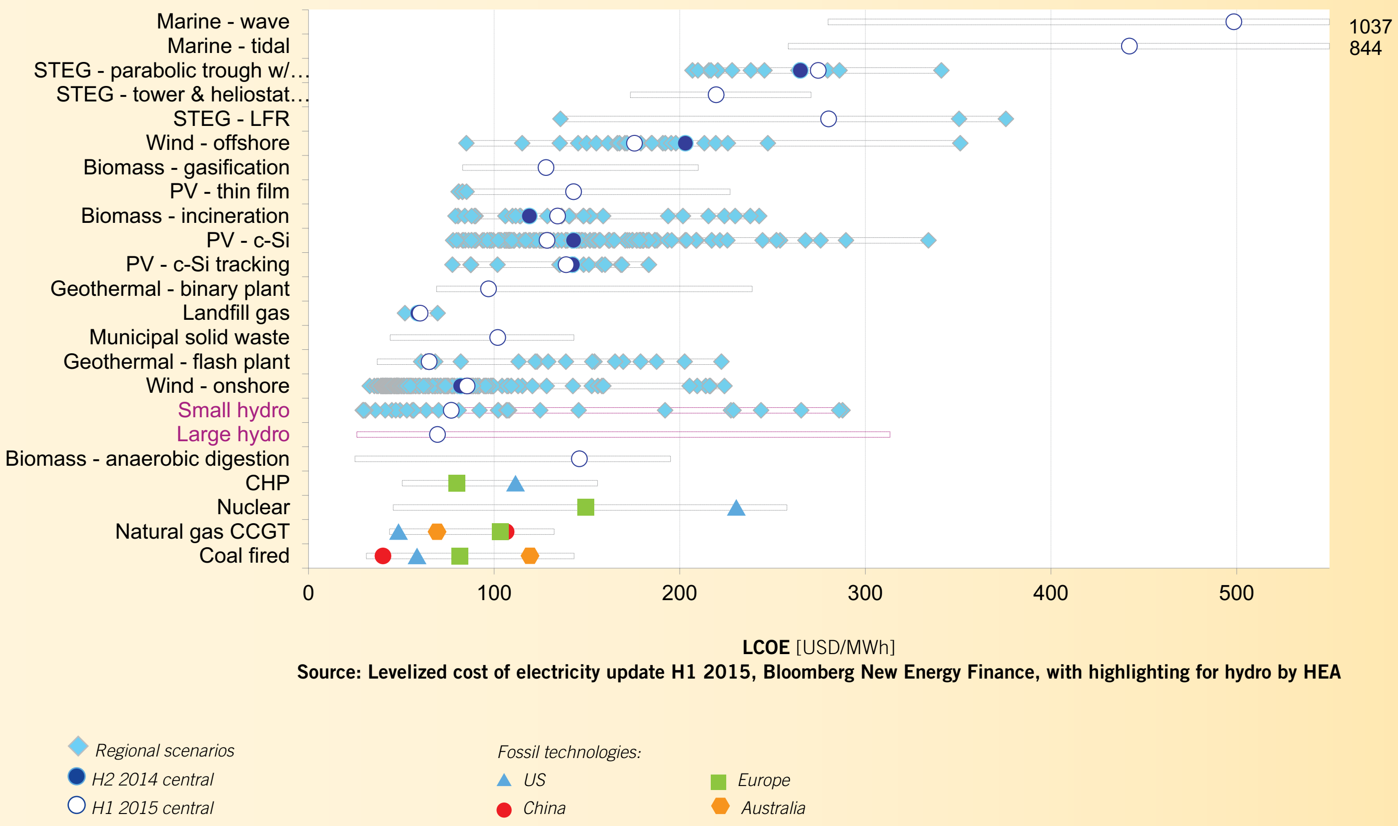


Figure 4: cost breakdown of a greenfield 500 MW plant in the US with 3,500 USD/kW capex [IRENA 2012]

Amounts expressed in cUSD/kWh	IEA (2012)[1]	IRENA (2012)[2]	Bloomberg New Energy Finance (2013)[3]
Currency base	USD_{2012}	USD_{2010}	USD_{2013}
Large hydro	2-23	2-19	6.9 (central estimate)
Small hydro	3.5-23 (“micro hydro”)	2-27	7.0 (central estimate)
Refurbishment / upgrade		1-5	



Source: Levelized cost of electricity update H1 2015, Bloomberg New Energy Finance, with highlighting for hydro by HEA

Box 3: Cheap hydropower: cost estimates [top]. Hydro has the lowest LCOE of all technologies and the central estimate for hydro LCOE is among the lowest. Bloomberg surveyed the industry in the second half of 2014 [H2 2014] and the first half of 2015 [H1 2015]. The central estimates marker indicates the average LCOE for each technology.

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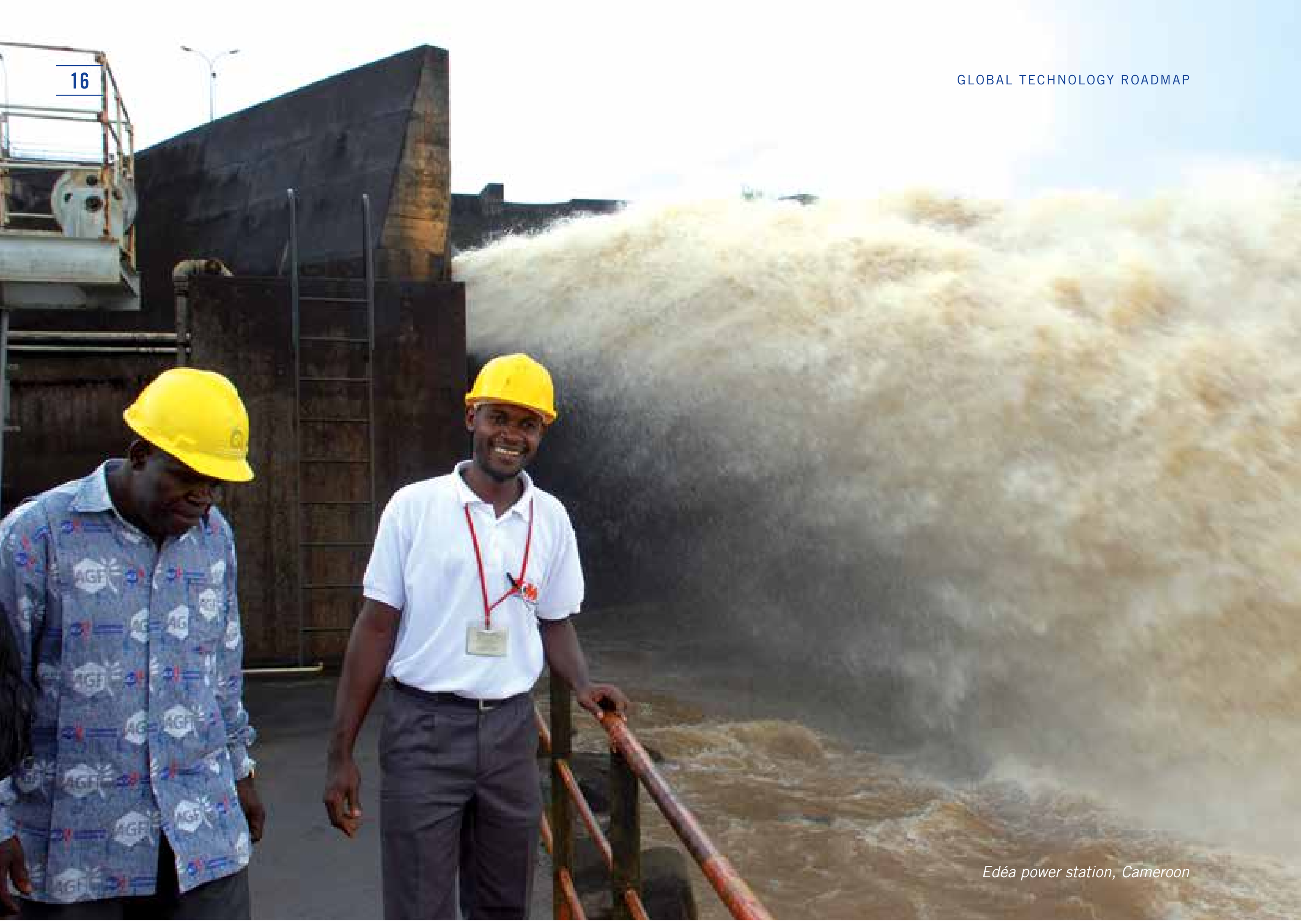
[1] [IEA 2012]
[2] [IRENA 2012]
[3] [BNE 2014]



Edéa power station, Cameroon

MULTIPURPOSE BENEFITS OF HYDROPOWER

Hydro's sustainability story is not just one of damage mitigation but also of net social and environmental improvements. Hydro projects can create external benefits such as flood protection, better river navigability, water conservation and, depending on the constraints under which the plant is operating, flows of water that are an improvement, ecologically-speaking, on the pre-existing situation (Box 4). The second largest producer of hydroelectricity in the US, the Bureau of Reclamation, started its life over a century ago with the mission of "irrigation; flood control; and water for domestic, industrial and municipal use" with hydropower "generally being a secondary purpose" [BUREAU 2014].

Example 1

The Baba Multipurpose Project in the Los Ríos province of Ecuador transformed the lives of local people even before commercial operation began in 2013. The dam mitigates flooding and helps prevent erosion during the rainy season over about 20,000 hectares in the Buena Fe.

Example 2

The weir in the Czech town of Litoměřice was replaced in 2012 with a small hydro power plant and a fish pass. The weir had blocked fish migrating upstream, but the fish pass (part-funded with EU money) now allows them to reach new spawning grounds. The installation will be replicated 20 km upstream.

Box 4: Examples of multipurpose benefits of hydroelectric projects

Hydropower equipment manufacturers — a partner for local economic development

Hydropower equipment manufacturers help to ensure that substantial direct economic benefits accrue to populations living close to sites of hydro construction or refurbishment (Box 5).

In the Rouna II refurbishment in Papua New Guinea, the total contract value was divided 65/35 in favour of the local portion (locally-sourced labour, supplies and services). Also, Andritz Hydro invested in the training and development of personnel.

Box 5: Local economic benefits of the Rouna II refurbishment, Papua New Guinea

TRAINING CENTRES

Southeast Anatolia is the region in Turkey with the country's highest youth unemployment rate. In the town of Mardin, Andritz Hydro has built a training centre accepting 36 apprentices per year in metalworking, basic electrical engineering and welding. Andritz Hydro shouldered the costs of constructing and equipping the centre and is covering its running costs for the first three years, including stipends to the trainees. The first trainers came from Austria in 2012. Teaching alongside them (and learning from them) were staff from the Technical Institute in Mardin (Figure 5). The local staff is now helping to train the next cohort of apprentices in preparation for the time when Andritz Hydro hands over responsibility for the centre fully to the Institute.

Figure 5: Opening ceremony of the Mardin Training Centre in the presence of ministers from the government of Turkey and Austria officials

Figure 6: Graduates of Escola Formare in 2013

Voith has also invested in training centres, for example near its manufacturing centre in Manaus, Brazil. Working with SENAI, the National Industrial Learning Service, it has taught welding, boilermaking and machining to men and woman in the state of Amazonas. The Manaus centre teamed up with CIEE (Company-School Integration Center) to offer apprenticeships. Some of the apprentices are later hired as employees.

Through its "Escola Formare" programme, initiated in 2008, GE offers apprenticeships to disadvantaged young people from the Taubaté region in Brazil. GE employees, eager to share their experience and knowledge, deliver theoretical and hands-on training with a focus on manufacturing techniques. The apprentices graduate after one year, equipped with the skills for careers at GE or one of many industrial companies in the region (Figure 6).

CREATION OF EXPORT OPPORTUNITIES

The outside-Europe manufacturing sites of hydro equipment manufacturers do not exist purely to serve local markets. For example, over the last five years, the manufacturing sites of HEA members outside Europe and North America on average derived between a quarter and a third of their revenues from export. This is true also for the sites located in BRICS.

OVERALL EMPLOYMENT BENEFITS

IRENA has calculated that hydro will be a major source of employment in 2030 for the 26 countries considered both under its reference scenario and under its REMAP 2030 scenario (explained in Box 3). Under the reference scenario, it employs the second largest number of people after bioenergy and under the REmap 2030 case it is the third largest employer behind bioenergy and Solar PV (Figure 7).

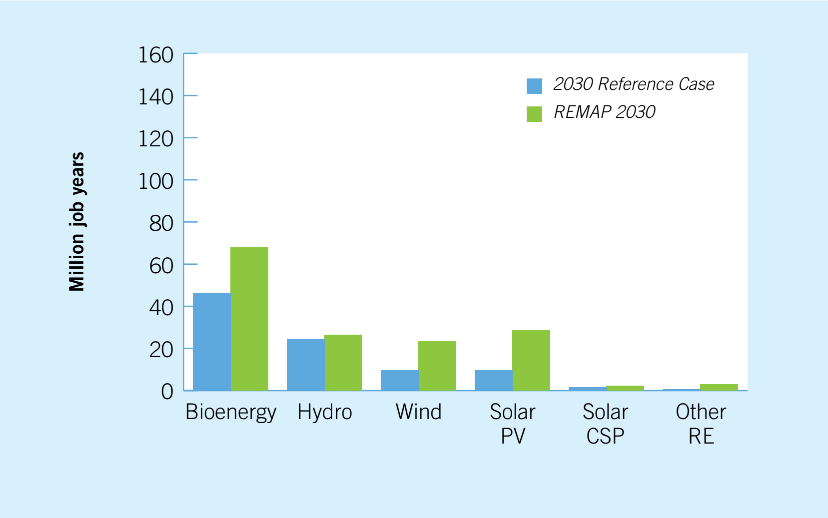


Figure 7: Direct global employment effects by renewable energy technology, cumulative 2013-2030 [Adapted from IRENA 2014]

Ever better performance, ever higher quality

Hydropower is a mature technology. The machines deployed today have been perfected over more than 150 years. Power output, power density, size, and efficiency have increased. Material development has led to steels that are tougher and more corrosion-resistant. Overall quality has improved enormously thanks to work in the laboratory and in the foundry.

Nevertheless, further developments and applications in material research are expected. Environmental aspects (detailed later) will continue to push technical development, for example with oil-free hubs in Kaplan machines. With a view to meeting the demand for more output, technology for longer lasting generator insulation, cooling and increased robustness will be pursued. Developments in power electronics and superconductor technology will be monitored in order to integrate the right elements at the right time.

Hydro equipment manufacturers are responding to the request of their customers for increased flexibility, more frequent load changes and greater availability.

Pelton runner undergoing a turning process during manufacture

PRECISION ENGINEERING...

Generally, for larger plants (output >15-30 MW) hydro equipment is custom-designed. This allows optimizations to be found that could boost performance by 0.1%, which is enough to make the effort worthwhile. In smaller plants, engineering costs outweigh potential extra revenue, so modular solutions are the most cost-effective.

Computer design, modelling and simulation

Hydro equipment manufacturers have been quick to exploit the increase in computer speed and in the quality of computer-aided engineering tools. Computational Fluid Dynamics (CFD) has progressed from allowing 2D flow analysis in 1975 to simulating multiphase flow and fluid structure interaction 40 years later. The application of Finite Element Method (FEM) techniques advanced from rotor dynamic analysis to forced response analysis, and from analysis of a single component to analysis of a complete system (Figure 8). Computer tools are used to find designs that avoid vortices and related pressure pulsations and cavitation caused by the movement of water through the turbine (Figure 9).

Figure 8: 40 years of computer-aided engineering – from analysis of a single component to a joint analysis of a complete system.

They are also used for optimising the interaction of the electromagnetic field of the generator's rotor with the stator and to predict the build-up of heat in generators and the flows of cooling air or water needed to keep temperatures down. The pole end plates of generators, which are mechanically highly loaded components of a generator, are a recent example of how improved design and the use of high quality materials have increased lifetime tremendously.

Computational techniques were used in the refurbishment of the Pelton turbines at Mayrhofen hydropower plant, Austria, in 2012. The result was an increase in the peak power of each of the five turbines from 60 MW to 67.5 MW and a 3.5% increase in weighted efficiency (Figure 10).

Figure 9: Simulation of turbulent sub-structures downstream of a Francis turbine

Computers have not replaced tests using scaled physical models. The tests are needed for verification and confirmation during the design process and represent a unique form of risk minimization for hydro equipment customers.

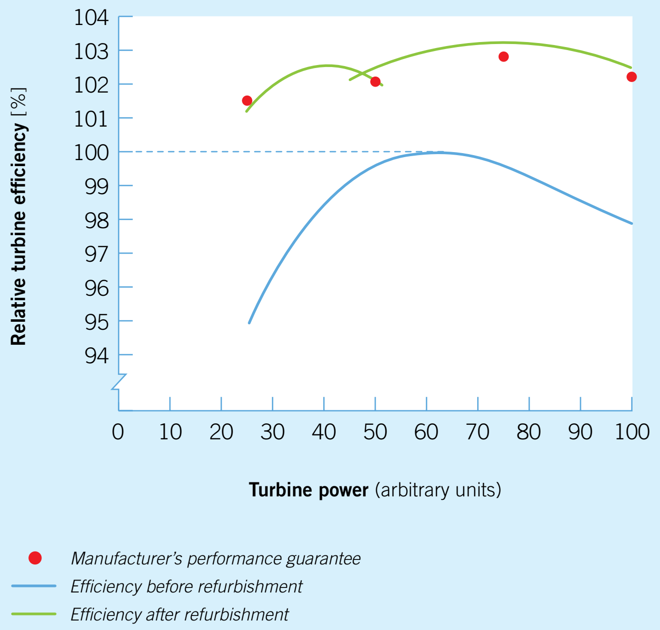


Figure 10: Mayrhofen efficiency improvements after refurbishment in 2012 – notice the flatter curve: peak efficiency over wider MW range.

Technology outlook

The improvement of computer tools remains a topic of intense research. The aim is by 2030 to model the following with complete confidence:

> Stochastic variations in flow patterns (turbulence models)
> Pressure pulsation
> Rotating stall
> Dynamic system behaviour and resonance between the turbine/generator system and the electrical and hydraulic system.

In addition, improvements are needed in the modelling of:

> Fluid-structure interaction (by 2020: CFD, FEM and models of the interactions between water and the turbine structure yield reliable lifetime predictions for any load)
> Air cooling of generators (by 2030: greater accuracy with 10% of today's computer power or time).

HEA members are, in some cases, working with universities to develop these models.

Pa Tien small hydropower plant, Taiwan

...ADAPTED TO LOCAL CIRCUMSTANCES

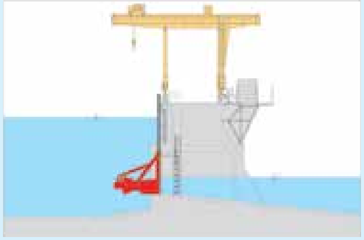
Small hydro for kW-scale up to tens of MW

Small hydropower plants – grid-connected or not – are a cost-effective way to provide electricity. The technology is easy to operate and maintain. Most of the world's small hydropower potential remains untapped. Growing demand is expected in South America and Southeast Asia, Africa and also Canada. These plants can provide voltage regulation which is a valuable (though rarely remunerated) grid service at distribution level.

Francis, Pelton and Kaplan designs are all scalable to small hydro power ranges. Francis turbines are the most common small turbine design, just as they are for large turbines but a variety of other designs specific to low power applications exist (Figure 13). Very often these low-power devices may be integrated into existing water infrastructure (Figure 11).

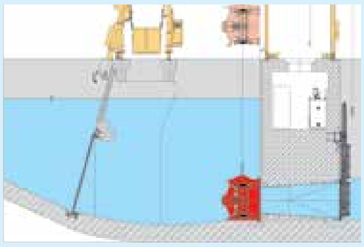
The design of small hydro turbines is driven by a need for minimal maintenance, low delivery times and ease of installation. Manufacturers have responded

Application: irrigation dams



Jebel Aulia, Sudan
operational 2004;
80 units = 30.4 MW

Application: shiplocks



Lower St Anthony Falls, US
operational 2011;
10 MW

Figure 11: Integration into different examples of existing water infrastructure

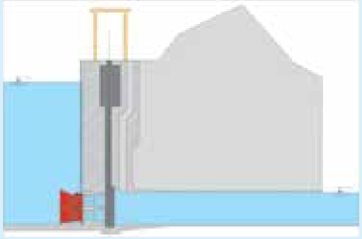
Figure 12 Illustration of Voith's StreamDiver™

by delivering devices pre-assembled in arrays for very low head sites. Andritz Hydro's HYDROMATRIX® technology and Voith's StreamDiver™ consist of multiple identical Kaplan bulb turbines in an array facing the water flow (Figure 12). Their advantage is that individual turbines in the array may be retrieved for repair or in case of imminent flood conditions. Also, depending on the river's discharge at any given moment, different numbers of turbines may be switched on, allowing the discharge through one to be at the optimal level (Box 6).

> Andritz Hydro's HYDROMATRIX® technology was chosen in preference to conventional bulb turbine for the 53 MW Ashta I and II project in Albania. It offered the lowest overall construction costs while also offering the lowest LCOE and meeting the condition of no change to the water levels in the surrounding plains.

Box 6: Choice of an array technology over a conventional bulb turbine in Albania

Application: intake towers



Colebrook, US
operational 1988;
3 MW

Application: navigation dams

Concept;
85 MW

A solution for every small hydropower site

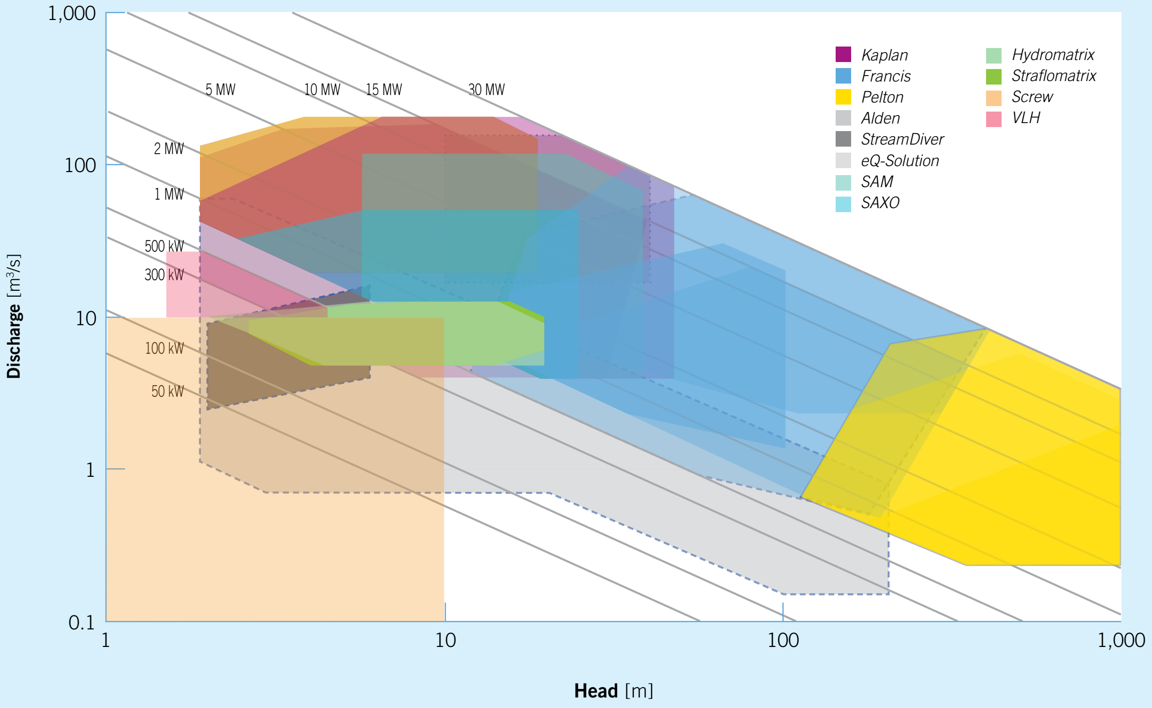


Figure 13: Generic and manufacturer-specific technologies mapped on a chart of discharge against head. The chart shows the products of HEA full and associated members (manufacturers of large and small equipment) – allowing a suitable design to be found for almost any site.

Technology outlook

Bulb turbines make up 2% of all turbines installed by capacity, but 7% of all turbines in small hydro projects. While fixed-speed bulb turbine technology is well understood, variable-speed bulb turbines that operate under extremely wide head ranges (1-6 m) and bulb pump-turbines are new development avenues. They may facilitate, and be driven by, the take-off of novel forms of pumped storage, such as offshore lagoons.

In Europe, the Network Codes to be published by ENTSO-E (the umbrella organization of the European transmission system operators) will put stricter conditions on the fault behaviour of generators including small hydro power plants. Technology will be developed in order to comply. More generally, the Network Codes define the requirements for different classes of generators for grid connection.

Small hydropower plants providing rapid regulation of frequency, voltage and active or reactive power will become valuable sources of flexibility in ‘virtual power plants’.

XXL machines

Large projects attract a lot of public attention and a spotlight is put on their environmental profile. The IEA has highlighted that the ecological impact per MWh of production can be less for large projects than for small ones.

Bigger units are intrinsically more efficient. A machine with a 10 m runner, such as the one installed at Xiang Jia Ba in China, is 0.1% more efficient than a machine with the design scaled down to 8 m, because in larger machines, flow friction losses are relatively smaller (higher Reynold's number). On a 800 MW turbine, this could equate to the annual generation of a 2-MW onshore wind turbine. Economies of scale are achieved in the manufacture of larger units.

770 MW Francis runner for Guri II (Simón Bolívar), Venezuela

Because multiple versions of the same machine are installed at Giga-project sites, economies of scale related to manufacturing volume are also captured.

Technology outlook

The performance of very large hydro units could be improved by using stator winding voltages in the range of 24-25 kV. Today's maximum is 23 kV.

TECH CORNER 1

Giga-projects in figures

Xiang Jia Ba (2012)	Xiluodo (2013)	Tomorrow's Giga-project
• **Turbine:** 800 MW • **Runner diameter:** 10 m • **Generator:** 889 MVA, air-cooled with 23 kV windings (world first) • **Generator rotor:** diameter: 19 m; height: 3.5 m. • **Load on thrust-bearing pads (axial load):** 4,300 tonnes, of which runner mass: 400 tonnes. Thrust-bearing technology: double-layer	• **Turbine:** 784 MW • **Runner diameter:** 7.7 m • **Generator:** 855.6 MVA (air-cooled) • **Generator rotor:** diameter: 13.7 m; height: 4 m. • **Load on thrust-bearing pads (axial load):** 5,000 tonnes, of which generator mass: 1,350 tonnes. Thrust-bearing technology: magnetic	• **Turbine:** >1 GW machines expected imminently; 1.2 GW machines before the end of the decade (besides the technical challenge, few suitable sites exist). • **Runner diameter:** dependent on head. Smaller than Xiluodu or Xiang Jia Ba if head > 200 m • **Generator:** 1,100 MVA with 24-25 kV windings, likely 99% efficient

Hydro-abrasive erosion

Hydro equipment can be adapted to many kinds of watercourse including those that carry a high concentration of hard particles. Highly particle-loaded rivers are typical of the Himalayan region but flow from most young geological formations, including the Alps and Andes (Figure 14).

Even particles below 0.1 mm in diameter, especially hard and angular ones such as quartz and feldspar, can harm certain turbine parts, quickly abrading surfaces and causing the turbines to become less efficient. Surfaces exposed to a high relative water velocity are damaged the most. For Francis turbines, the eroded parts are mainly the guide vanes, facing plates, labyrinths and runners; for Pelton turbines, they are the runners and injectors. These parts may need to be treated almost as a consumable and overhauled or even replaced after each flood season.

One solution to protect the equipment in highly particle-loaded rivers is to shut down the hydropower plant during periods with the highest particle concentrations but this of course leads to significant generation losses. A more sophisticated solution is to use protective coatings on runners (Figures 15, 16, and 17). These increase the time between overhaul by a factor of between two and five and reduce the damage to some specific turbine parts by an even greater amount. Longer periods of operation imply higher generation, helping investments in minimizing damage from hydro-abrasive erosion to pay off quickly.

Figure 14: River in the Andes carrying large quantities of particles to the Alfalfal hydropower plant, Chile.

Figure 15: Coating of a Pelton runner using the high velocity oxyfuel process (HVOF). The average thickness of the coating is 0.3 mm.

Pelton turbines are particularly exposed to hydro-abrasive erosion because of the high speed at which particles strike the runner buckets, but they tend to be installed in preference to other kinds of turbine because their runners are easier to replace.

Precautions against hydro-abrasive erosion are ideally taken at the time the plant is designed. It is often not possible or expensive to correct its effects afterwards. This means designing hydropower plants in a profit-maximising way from a layout, hydraulic and mechanical perspective. For example, features may be incorporated that prevent particles from ever reaching the turbine or reducing their velocity when they do (Table 1). Most measures have an impact on investment costs and / or on efficiency, making careful analysis of investments, operating costs and future power production crucial.

HPP layout	• Desander • Location and geometry of intake • Turbine type and number of units
Hydraulic layout	• Reduction of relative velocity • Minimization of cavitation • Design to minimize damage from hydro-abrasive erosion • Designs allowing easy application of the coating
Mechanical design	• Better overhaul possibilities • More stable design / construction
Protective coating	• Use of high-quality coating • Fully robotic application, if possible

Table 1: Hydro-abrasive erosion may be combatted in a variety of ways

Uncoated Pelton runner after 38,000 t of particles have passed through the turbine.

Pelton runner with standard coating after 120,000 t of particles have passed through the turbine.

Pelton runner with latest coating technology after 183,000 t of particles have passed through the turbine.

Figure 16: The amount of particles passing through the turbine before significant damage occurs may be increased by a factor of two to three for a standard coating and by a factor of five using the latest technology, as shown here for a Pelton runner from the Alfalfal plant, Chile.

Figure 17: The possible extent hydro-abrasive erosion was not known at the time the runner on the left was installed at the Nathpa Jhakri plant, India. Its only protection against erosion was a desander. It was replaced by a runner designed to be fully coated by robot. The runner for the power plant upstream (Karcham Wangtoo, right) was designed with the same requirement in mind, and additionally for ease of replacement, by allowing the generator to remain in place.

Technology outlook

The importance of increasing plant lifetime under erosive conditions will increase as attempts are made to harness the hydropower potential of areas with high particle loads. Holistic approaches to minimize erosion-related damage will increasingly be used. In the past anti-erosion measures were sometimes taken too late.

Turbines will become more resistant to erosion and turbine designers will be better able to predict how erosion occurs. In coating technology, work will focus on methods for applying coatings (for example, to ensure all relevant turbine parts are protected) rather than on coating formulas.

Figure 18: GE Oceade™ 18 - 1.4 MW, three-bladed hydrokinetic turbine used for capturing energy from tidal currents

Harnessing the tidal-stream resource – a new frontier

In the past ten years, hydro equipement manufacturers have become active in developing hydrokinetic turbines (Figure 18), which are deployed in subsea tidal streams to capture energy from the flow of water through natural channels. This technology, deployable at depths of 30-100 m, affords predictable electricity production up to 20 hours a day.

Since 2013 each of the three HEA full members has tested a 1 MW tidal stream device in Scottish waters. In total, considering both wave and tidal stream devices, 15 MW have been deployed worldwide (in Europe, China, Australia, Canada and Korea) as single test devices. This industry is still in its infancy, with costs higher than those of most other renewable energy technologies, but with significant potential for cost reduction.

The sea, particularly the parts of it where currents are strongest, is one of the harshest environments on the planet. Hydrokinetic turbines are therefore designed for

> ease of installation, meaning without divers (remote-operated vehicles are used instead)
> enhanced reliability to increase the time between maintenances
> quick swapping in- and -out of turbines in a short window

and include

> instrumentation for detailed condition monitoring in order to anticipate and optimize maintenance activities.

Technology outlook

A sign of just how young this industry is, is the diversity of possible approaches to turbine regulation, around which there is strikingly little industry consensus: the choice of one manufacturer is for fixed-pitch blades with a symmetric profile avoiding the need to pitch and yaw; the choice of another is indeed to include a blade pitching mechanism and a nacelle-yawing system. There is, however, convergence on the 'wind turbine-like' design.
Arrays of up to 50 MW are expected in Europe by 2020, which will demonstrate the connection to the grid of multiple turbines and understand the hydrodynamics interactions between turbines. By 2025 the technology should generate electricity at a cost that is competitive with widely deployed forms of renewable energy [OCEAN 2013]. Tidal stream device development faces some of the same challenges as offshore wind development. Know-how will spread between the two sectors. There is also the potential to apply ideas from small hydropower to tidal stream devices and vice versa.

More MWh through refurbishment

Hydro equipment ages due to wear and tear. Aging is accelerated by certain plant operation regimes (particularly low-load operation – Figure 25 – page 36), the passage of large quantities of silt, and corrosion due to the presence of pollutants. The typical lifecycle of equipment is given in Figure 19.

The good news is that refurbishments to restore or upgrade a plant's performance are possible and as Box 3 (page 15) showed, highly cost-effective. In an upgrade, capacity is increased. This is often cost-effective if minimal civil works are needed.

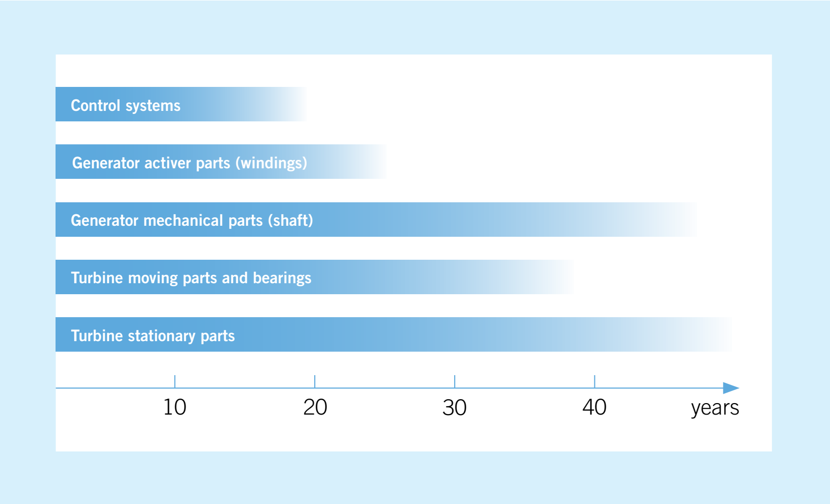


Figure 19: Typical component lifetimes. Faded tails indicate spread of typical lifetimes.

TECH CORNER 2

As Figure 19 shows, components related to plant control need typically to be replaced first. Frequent maintaining or improving of this equipment is a highly cost-effective way to ensure the plant's availability, reliability and safety.

Electrical components have somewhat longer lifetimes. For example, the insulation material in the generator, exposed to temperatures in the range 50-110°C (and to temperature fluctuations) for much of their life, disintegrates. The following typical capacity increases may be expected for different generator upgrades:
Mechanical aging is a slower process, and slowest for the stationary parts of a turbine.

Today's monitoring systems are used mainly to avoid equipment failure, not to optimize maintenance intervals. Optimization would reduce unnecessary downtime to zero, resulting in an increase in revenue.

Upgrades of…	Typical / possible capacity increase
Stator winding	5-10%
Stator winding + stator core	7-15%
New stator + new pole winding	10-20%
New stator + new poles	10-25%

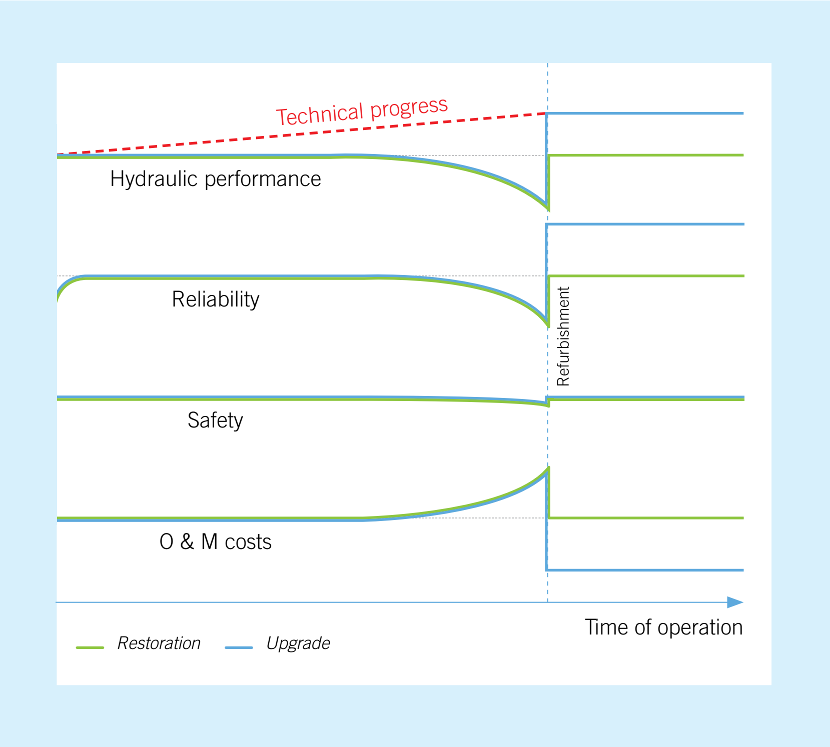


Figure 20: Plant performance declines and running costs increase due to wear and tear on plant equipment. Plant output may be restored or upgraded when losses become large enough to justify the investment.

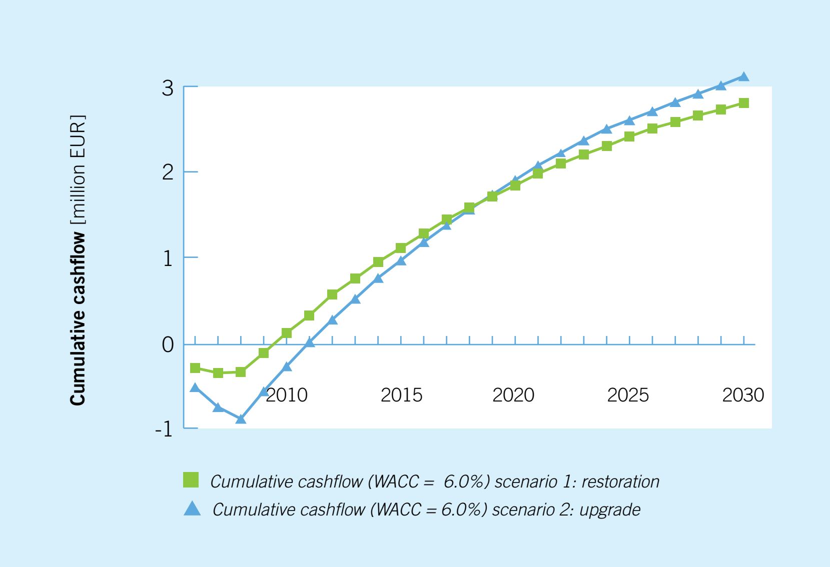


Figure 21: Modelling for the Klammstein plant, Austria: refurbishment pays back quickly. Upgrade is more profitable than restoration after 13 years.

The cost-effectiveness of both options was compared for the refurbishment of the 7.6 MW Klammstein plant, Austria, in 2008 (Figure 21). In the case of restoration of performance to its original level, only 3.5 years would be needed to recover the investment costs. In the case of performance upgrade, 5 years would be needed, and after 13 years, this option was expected to be the more profitable.

REFURBISHMENT EXAMPLES

The turbine and other equipment of the 1960s-era Cambambe I plant in Angola were replaced in a four-year project that ended in December 2012. The plant's peak output was boosted by 40%.

At the Akosombo plant in Ghana, six new runners were fitted and other components modified. Altogether 25% was added to the plant's power output and efficiency was increased across the operating range, with maximum efficiency 5% higher than in the original plant (Figure 22). During 2006-2010 four units dating from 1964 were replaced at the Infiernillo plant in Mexico. Their output was increased by 28%. A similar increase in output was achieved at the Outardes III plant in Canada. For such increases to be possible without an expensive modification of civil works, the pre-existing structure of the plant had to allow higher discharge rates.

At Toyomi in Japan +10% output was achieved by swapping the 1952 Francis turbines for a vertical bulb turbine having the largest runner and generator for a bulb turbine anywhere in the world. The turbine has an oil-free runner, preserving water quality.

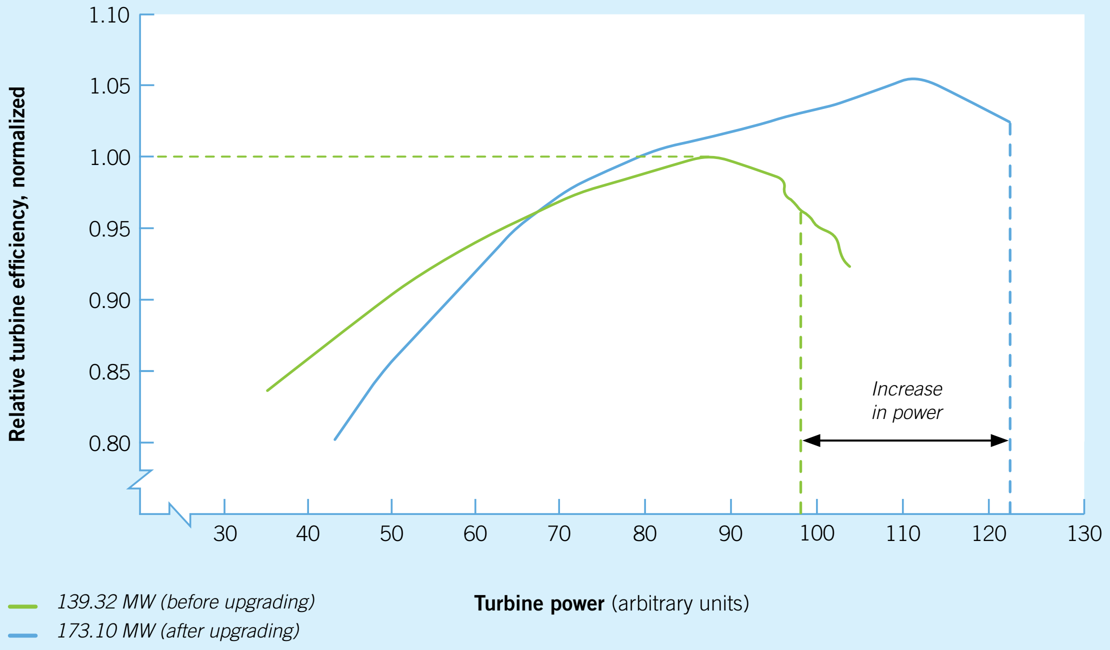


Figure 22: Curves like this one for the Akosombo plant, Ghana, are typical of the plant performance before and after an upgrade.

TECH CORNER 3

Building a new hydropower plant or refurbishing one can be a logistical challenge, with suppliers required to meet tight deadlines or to keep one or more units running while work on the others takes place. Refurbishment project outages can be in the range of weeks to a year or more depending on the scope of the refurbishment.

Hydro equipment suppliers are experienced in overcoming these obstacles, arriving at site- and situation-specific solutions. They can move heavy equipment on unsealed roads or to almost inaccessible locations (Rouna II, Papua New Guinea); cope with an absence of skilled labour or the need to import almost all materials or disruptions to the project schedule (like time needed to remove landmines from the site of the new spillway for Cambambe I or cross-cultural differences of opinion on the importance of punctuality). They can work with legacy equipment (Guri II, Venezuela), and find innovative ways to make progress in freezing conditions (Budarhals, Iceland).

Project teams are sometimes spread across different continents. Differences in time zone can work to the team's advantage: as one team sleeps the other works.

Technology outlook

There are three major fields of technology development:

> **Operation and Maintenance**

Monitoring systems that, in combination with algorithms that take account of intervention history and knowledge of the component's design, determine the right moments for maintenance action. The importance of these will continue to improve. The potential for reducing outage time with intelligent monitoring systems is estimated to be 20%.

> **Power density (power per volume)**

In many cases refurbishment projects also increase the water discharge. To capture the power increase new hydraulic turbine designs and stronger mechanical components are needed.

Faster rotating machines are smaller than slower rotating machines of equivalent power, which creates the potential for savings in generator cost. The upper limit on generator rotational speed rises with the mechanical strength of materials used.

Higher power density also means that higher temperatures are reached in the generator. This is a challenge for the winding insulation material and generator design. Air-cooling of generators, which is cheaper to implement than water-cooling requires heat transfer techniques that get around the tendency of electrical insulators also to trap heat.

> **Efficiency**

With intense use of various computer-aided design tools, the efficiency of turbines and generators will increase, thereby increasing annual energy production.

Pantabangan lake, Philippines, showing dam, spillways and power station.

Hydropower – #1 for a stable grid

Grid operators are responsible for maintaining quality standards in the electrical grid. Large fluctuations of voltage and frequency, if they occur, damage electrical devices and facilities. Blackouts – whether planned or unplanned – can be extremely disruptive and costly for society.

Hydropower and its undisputed flexibility contributes to the stability of the grid in the following ways

> Hydro is dependable. In countries with weak grids and other significant generating assets, a hydro plant can provide a stable source of power.

> Many hydropower plants have “black-start capability”, i.e. they can be the first generators to provide a steady frequency during the re-establishment of the grid after a black-out.

> The inertia of a synchronous rotating generator damps the momentary rises or falls in grid frequency caused by grid load falling or rising.

> Hydropower can control reactive power, thus ensuring that power flows from generation to load. It also helps maintain voltage through injecting or absorbing reactive power by means of synchronous or static compensation.

> Hydropower provides balancing power, supporting the integration of wind and solar energy (both rapidly growing sources of power – see below).

Average Annual Growth Rates of RES Capacity (2009–2014)

Wind	18%
Solar PV	50%
Hydropower	3.5%

Total capacity by the end of 2014

Wind	370 GW
Solar PV	177 GW
Hydropower	1,055 GW

Box 7: Average annual growth rate in cumulative capacity 2009-2014; Total capacity by the end of 2014 [REN21 2015]

> “Hydropower is useful for ancillary services and for balancing unstable transmission networks, as hydropower is the most responsive energy source for meeting peak demand.”
>
> – IPCC 2011

SUPPORTING THE INTEGRATION OF WIND AND SOLAR

Wind and especially solar photovoltaic power have grown enormously in the last 5 years (see Box 7) and have established themselves as capable generation technologies deployable at many locations across the globe.

With increasing shares of wind and solar generation, the value of hydroelectricity grows. Reservoir hydropower plants are dispatchable – able to react faster than any other generation asset to changes in demand. Hydropower is the ideal complement to variable renewable electricity generation.

The intense use of hydropower as balancing power is a growing phenomenon, which will become more common across the world. As solar and wind capacity is added to the world’s electricity systems, more and more often gigawatts of residual load may appear or disappear over short periods and sometimes with little warning. Hydropower plants may be called upon to provide balancing power, in other words to provide additional power within timescales of seconds, minutes or a quarter of an hour (Figure 23).

In anticipation of imminent adoption by ENTSO-E of Network Codes that will lay down rules for participants in balancing power markets, some utilities are already equipping their plants to offer shorter ramp times, better fault behaviour, etc.

1990

- Demand followed a predictable daily pattern.
- Thermal plants, also some hydro, operated steadily at best efficiency points.
- Some hydro capacity and some gas or oil-fired capacity was dispatched to meet peaks in demand.

2030

- Demand continues to mostly follow a predictable daily pattern (although demand-side management flattens the load curve).
- Wind and solar power provide major amounts of energy at uncertain times.
- Thermal plants are operated for fewer hours. Those that operate inefficiently at part-load or no-load have closed.
- In combination with gas-fired plants, hydro plants are operated to buffer wind and solar output with a view to minimizing the GHG emissions from the electricity system.

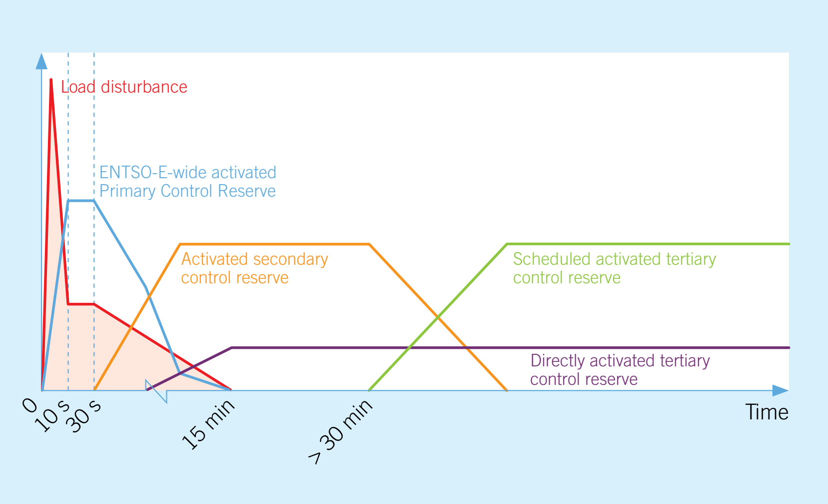


Figure 23: Frequency deviation causing the activation of power reserves in the specific case of Europe's transmission grid [ENTSO-E 2009]

Reservoir plants can supply balancing power, but so can low-head run of river plants using Kaplan turbines. As Figure 24 shows, this may imply operating them under a completely different regime from the one for which they were designed, leading in this case to more wear and tear on the turbine parts related to regulation.

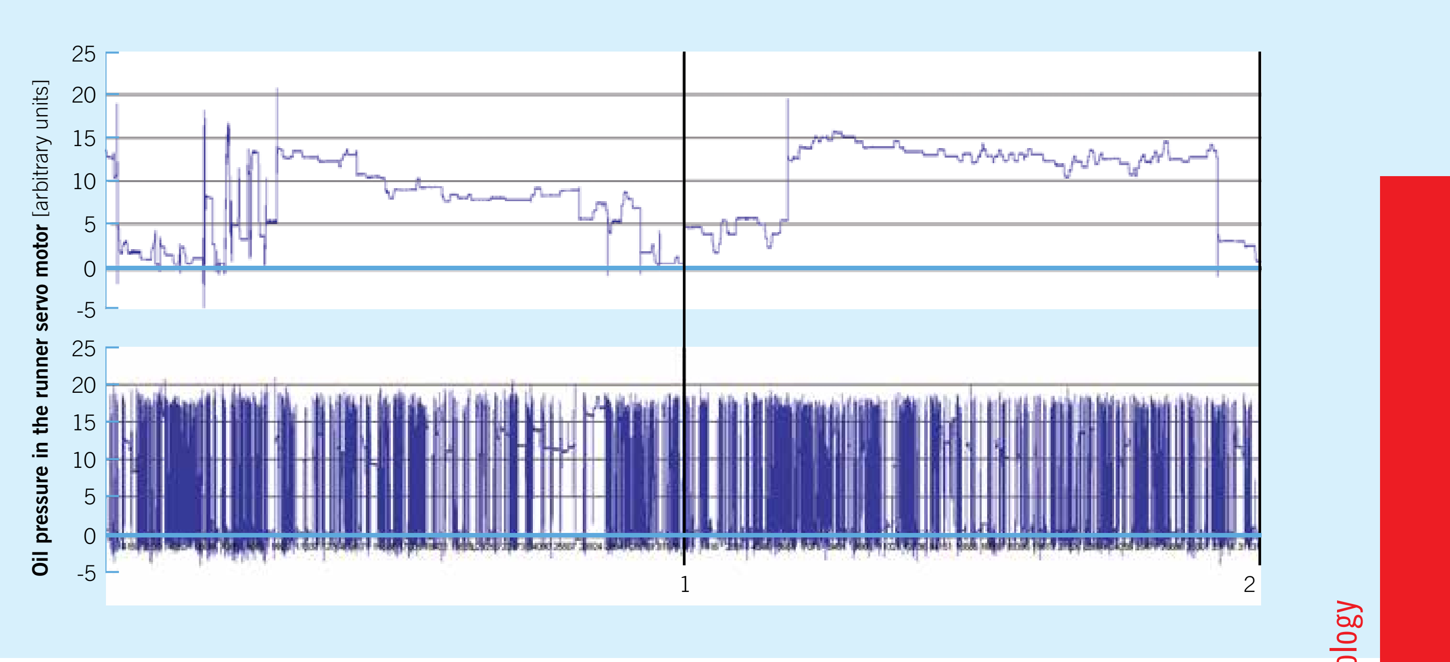


Figure 24: Differential oil pressure at the runner servo motor is an indicator of the rotary motions of the runner blades, which regulate water flow through the turbine. In the upper trace, the blades are being adjusted gradually to regulate water level in the river. In the lower, where the plant is instead being operated to provide second-by-second balancing power, they are changing position constantly. The horizontal axis spans two days at a Danube run-of-river station in Austria.

Technology outlook

Many hydro plants have not been designed to provide balancing power continuously. The biggest challenges are:

> frequent starts and stops (20 or more per day for pumped hydro in contrast to 3 per day formerly), and the mechanical and temperature-related stress they put on the stator winding insulation
> operating at deep part load and spinning reserve, and the related toll on the lifetime of components
> fast response, meaning adjustment of operating point several times per minute and the associated wear and load on the regulating mechanism
> voltage peaks due to the frequency converter, and their effect on the generator winding insulation.

Francis turbines and their close relations, pump-turbines, are the best performing turbine for heads in the range 50-700 m, making them the design most often installed. However they are intrinsically less regulable than either of the two other principal turbine designs, Pelton and Kaplan. To provide second-by-second control, turbines need to be spinning even if they are not producing electricity. Research is underway to make Francis turbines and pump-turbines less vulnerable to damage to the runner and turbine stationary parts under low or zero load, which creates highly turbulent flow (Figure 25).

Cavitation, draft tube pressure pulsations and vibrations are also likely under these conditions and should be minimized. The underlying physical mechanisms and the design parameters that affect their amplitude are being investigated.

A common challenge facing…

i) hydropower plants operated to provide balancing power over timescales of up to a minute,

ii) variable-speed PSP plants using frequency converters and

iii) high-voltage generators

…is to keep down the temperature of their windings effectively. By 2030, insulation materials will be able to withstand temperatures of 180°C for brief periods, allowing power output boosts of 10-15% for that time.

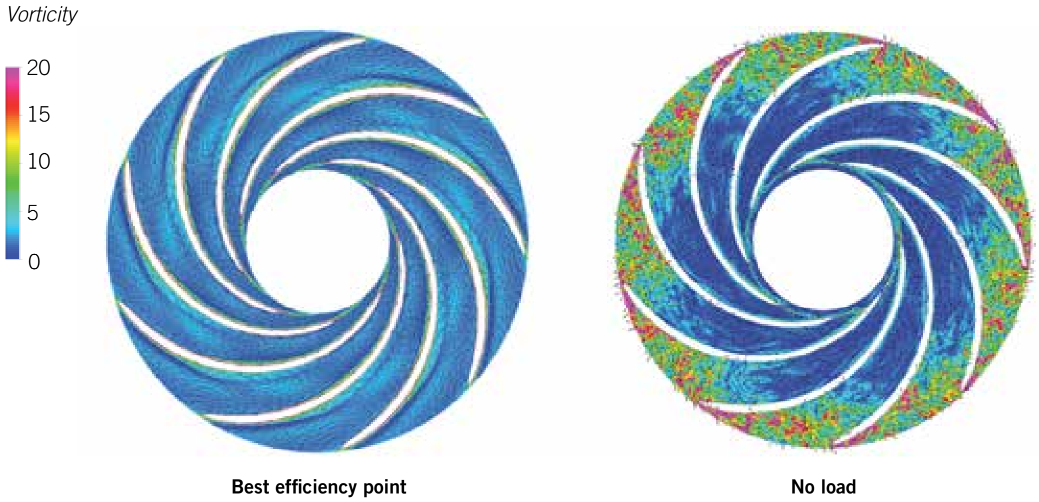


Figure 25: Turbulent flow in the runner (redder colors) does great damage to the runner blades. It occurs when a turbine is spinning at low load or at zero load. There is very little turbulence in turbines operating at their best efficiency points.

A Francis turbine in the workshop during the manufacture.

Pumped storage plants for efficient and cost-effective energy storage from hours to months

Pumped storage plants (PSP) were first deployed in the 1930s. They pump water from a lower reservoir to an upper reservoir when electricity prices are low, and regenerate electricity from the water flowing back downhill when prices are higher (Figure 26). Where neither reservoir receives natural inflow of water from a watercourse, the PSP is said to be "closed loop" (all the rest are "open systems"). Closed loop systems, which are initially charged from a nearby water body, are almost completely isolated from an ecosystem by being built underground, which simplifies their environmental permitting.

PSP achieves a round-trip efficiency of 80%. This compares favourably with other storage technologies especially when PSP's high power and storage capacity is considered (Figure 27).

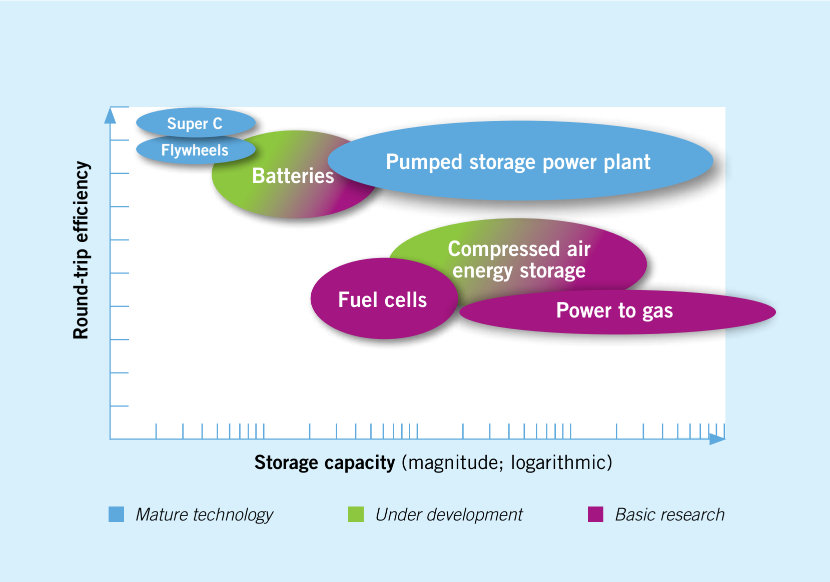


Figure 27: Comparison of electricity storage technologies. PSP is the only form of bulk electricity storage technology that today offers high efficiency and high capacity at low cost. 'Round-trip efficiency' is the electrical efficiency of the whole storage cycle from electricity to electricity at the grid connection point.

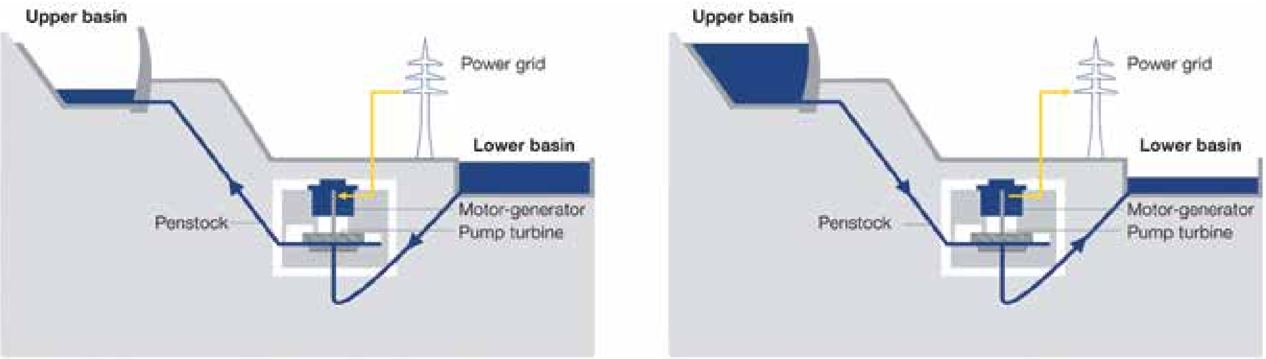


Figure 26: Principle of operation of a pumped storage plant (PSP); left: pumping (electricity storage); right: turbining (electricity generation)

12% of the world's installed hydro park is PSP. Japan (where 10% of the country's installed base is PSP) and Europe, which includes the Iberian Peninsula and the Alps, together account for most of the world's pumped storage capacity (Figure 28).

In Europe and the US, the role of PSP is increasingly to improve grid reliability (see Case Studies on two next pages). In Asia, where thermal capacity makes up a higher share of national energy mixes, the business case for PSP is rather founded on exploiting the differences in the electricity price that arise in periods of the order of one day, or portfolio optimization by utilities that own many different kinds of generation assets. The drivers in Europe can be expected to be seen in Asia in the medium term, however.

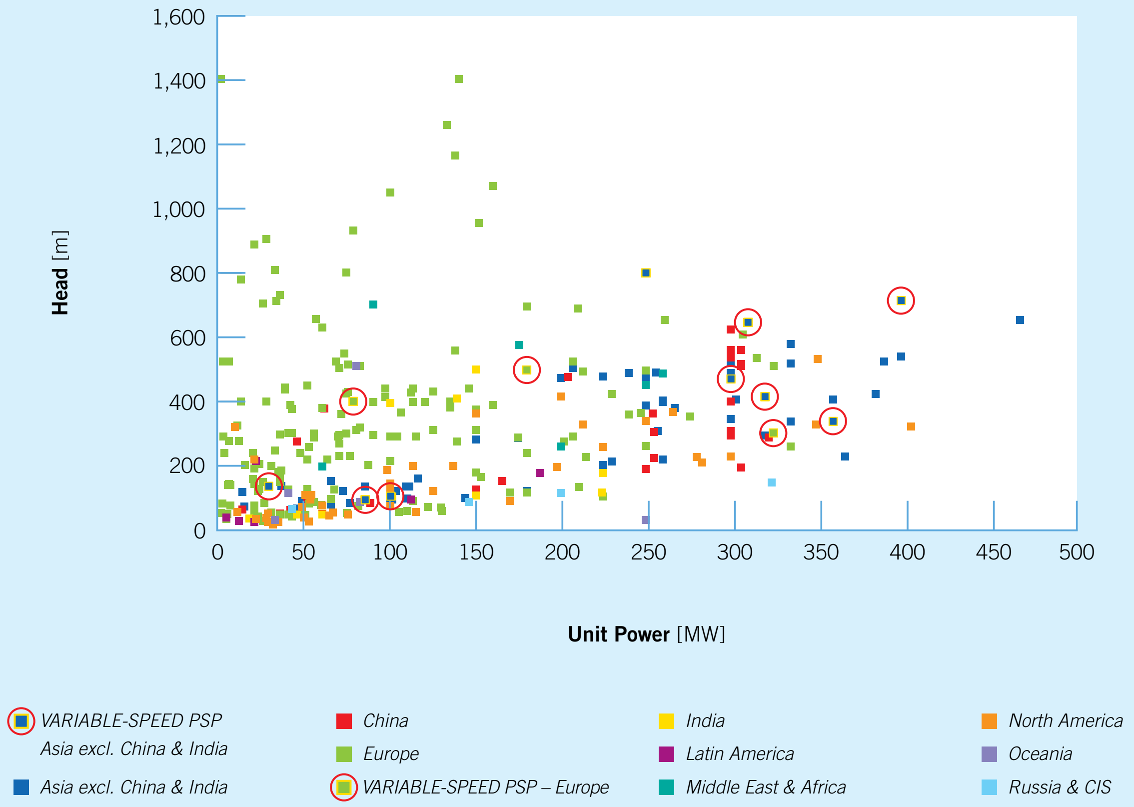


Figure 28: World installed base of PSP

CASE STUDY – EUROPE

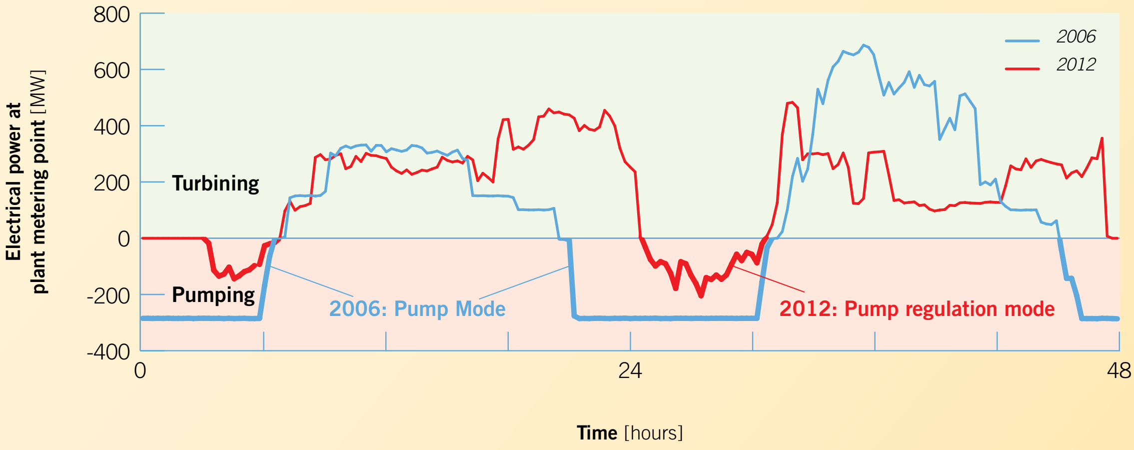
The Malta Hauptstufe PSP located in Austria, has a power system that is well integrated into that of Bavaria, a neighbouring region in Germany. In 2006 0.9 TWh of PV electricity was produced in Bavaria. By 2012, that amount was ten times greater and accounted for roughly 10% of all electricity consumed. This affected the way Malta Hauptstufe PSP was operated.

The chart below presents the output of Malta measured at the grid connection point on midsummer days in 2006 (blue line) and 2012 (red line).

2006: During the day the plant operates in 'classic' turbining mode, load-following around midday with up to four units turbining. At night, two pumps in the plant operate at full load for about six hours, so-called 'classic pumping'.

2012: Much higher PV generation in Bavaria means residual load is lower at midday, with peaks in demand (and plant output) instead occurring in the morning and evening. At night pumping happens in 'pump-regulation mode', meaning that the two pumps (or just one) operate at full load while other units operate in turbining mode. The summation of the pumps' and turbines' output therefore gives the appearance of a single adjustable pump at the grid connection point. Note that the plant's upper reservoir contains weeks' worth of storage. Over the period indicated, there was net outflow, but not enough to exhaust the reservoir.

Comparison of the operation of a PSP in Austria in 2006 and 2012 (27-28 June)



CASE STUDY – USA

Natural gas generation is used much more widely in the US to balance wind and solar intermittency than in Europe. With the US currently in a natural gas boom, PSP investments, including refurbishments, are being postponed, entailing the risks highlighted in Figure 20 (page 30). 90% of the 20 GW online today is 25 years old and designed for an era when only 2-3 stop-starts were expected per day. Accommodating variable renewable energy supply from wind and photovoltaics has required the plants to instead operate with 8-10 stops and starts per day. PSP naturally ages faster than pure-generation hydro and this new operation regime accelerates that process.

To draw attention to the value of PSP to the grid, the US's Argonne National Laboratory produced a study [ARGONNE 2014] showing that the addition of three variable-speed PSP plants (total capacity 3.1 GW) in the Western Interconnection (WI) grid would provide large shares of the expected demand for different ancillary services in 2022. For example, under a 'high wind' scenario, 13% of 'flexibility down' requirements could be provided, compared to 1% with the current 4.7 GW of fixed-speed capacity (Figure 29).

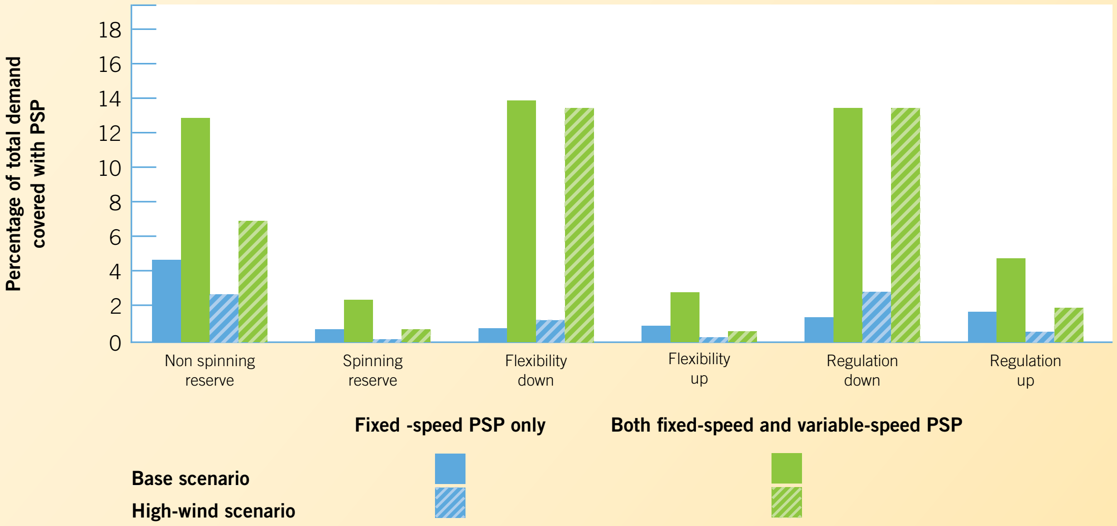


Figure 29: The horizontal-axis labels correspond to different kinds of balancing power. Particularly the capacity to 'down'-balance, where the plant absorbs power from the grid, is boosted with variable-speed PSP.

TECH CORNER 4

The trends in PSP technology are towards greater flexibility (stable operation over a wider range) and component robustness. These are supported by the following two major innovations:

Variable-speed PSP

Variable-speed PSP, first demonstrated Japan in 1990, has made it possible to pump at different power levels for a range of heads. Plants fitted with the technology absorb a range of power for any head, extending their ability to participate in ancillary services markets. The plants do this while retaining the capability of the older fixed-speed technology to turbine at a range of power levels for the same head.

Furthermore, variable-speed PSP…

- extends the lifetime of equipment by protecting it from rough operation and high dynamic load;
- offers greater partial load operation efficiency in turbining mode. The shape of the efficiency curve is flatter (Figure 30);
- offers higher output at low heads in turbining mode (Figure 31);
- by virtue of its tolerance to different plant topologies, it opens up the possibility of producing standardized PSP technology. This in turn means PSP can become cost-effective at smaller scales. Variable-speed could facilitate the emergence of novel applications like shoreline PSP;
- increases the potential sites for PSP plants. Fixed-speed plants require the maximum head to be at most 25% higher than the minimum head. This can be pushed to 80% with variable-speed.

The upgrade of a 250 MW pump-turbine in France to variable-speed, will enable it to regulate the power it absorbs within a 80 MW range (for example, by operating between 200 MW and 280 MW for a given head). This may allow the integration of several hundred MW of wind generation [HRW 2009].

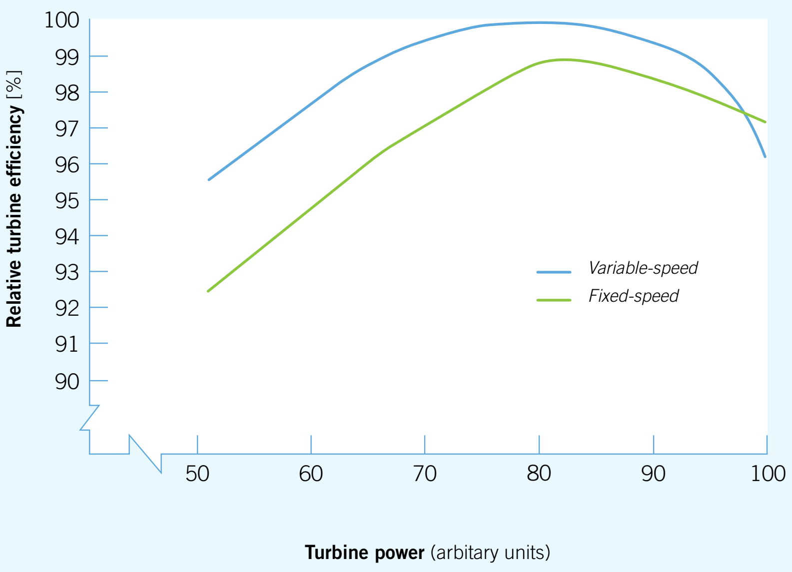


Figure 30: Turbine efficiency comparison

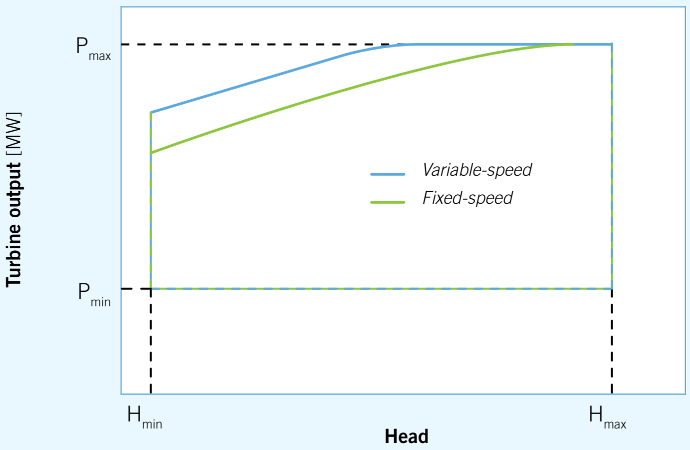
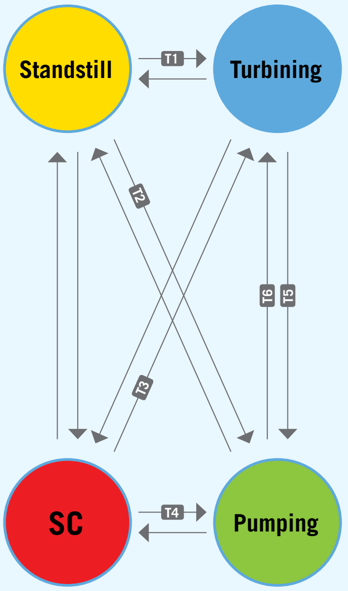


Figure 31: Turbine power comparison

Ternary machine sets

Most pumped storage plants have a turbine that ‘turbines’ when rotating in one direction and pumps in the other. A few have separate turbines and pumps connected on the same shaft, with the motor-generator in between (ternary units). Ternary units react faster than any other kind of pump-turbine to signals to switch from turbining to pumping (or vice versa – Figure 32), but they are also more expensive because they require an additional component (separate turbine and pump) and more civil works to accommodate the larger unit.



Pump-turbine				Time [seconds]				
T	Mode change			A	B	C	D	E
1	Standstill	→	Turbining	90	75	90	90	65
2	Standstill	→	Pumping	340	160	230	85	80
3	SC-Mode	→	Turbining	70	20	60	40	20
4	SC-Mode	→	Pumping	70	50	70	30	25
5	Turbining	→	Pumping	420	300	470	45	25
6	Pumping	→	Turbining	190	90	280	60	25

Reversible pump-turbine
A - advanced conventional (2012)
B - extra fast response conventional
C - variable-speed, DFIM

Ternary set
D - with hydraulic torque converter + hydraulic short circuit, horizontal, with Francis turbine
E - same as E but vertical with Pelton turbine

SC = synchronous condenser

Figure 32: Ternary units can switch from pumping to turbining and vice versa in a minute or less. The table was compiled in 2011 from data of some mode changes for some specific projects. Better values are obtainable from other projects.

Those that are equipped with hydraulic short circuit (a feature of the plant’s civil works) are additionally able to offer second-by-second control similar to variable-speed pump-turbines. In this mode, some of the pumped water never reaches the upper reservoir, but instead goes straight through the turbine. The torque supplied to the shaft by the turbine helps to turn the pump, along with the motor generator which is taking electricity from the grid. The pump is therefore able to operate at a fixed speed but still absorb varying amounts of net power from the grid. Sending water through this circuit necessarily implies losses, but these may be more than compensated by the value of the grid-balancing service that is being provided.

The Kops II PSP, Austria (Figure 33), consisting of 3 x 175 MW ternary units (pump mode 150 MW) is highly flexible and operates with up to 60 mode changes per day of less than 20 seconds.

Multi-stage pumps

A typical pump-turbine can pump to a height of up to ≈ 800 m. To reach higher heights, pumps are installed in series one above the other in the powerhouse, creating a so-called multi-stage pump or pump-turbine. This has enabled, for example, the Lac de l’Hongrin (5 stages; head: 850 m) and Nestil (4 stages; head: 1,060 m) both in Switzerland to be used for pumped storage.

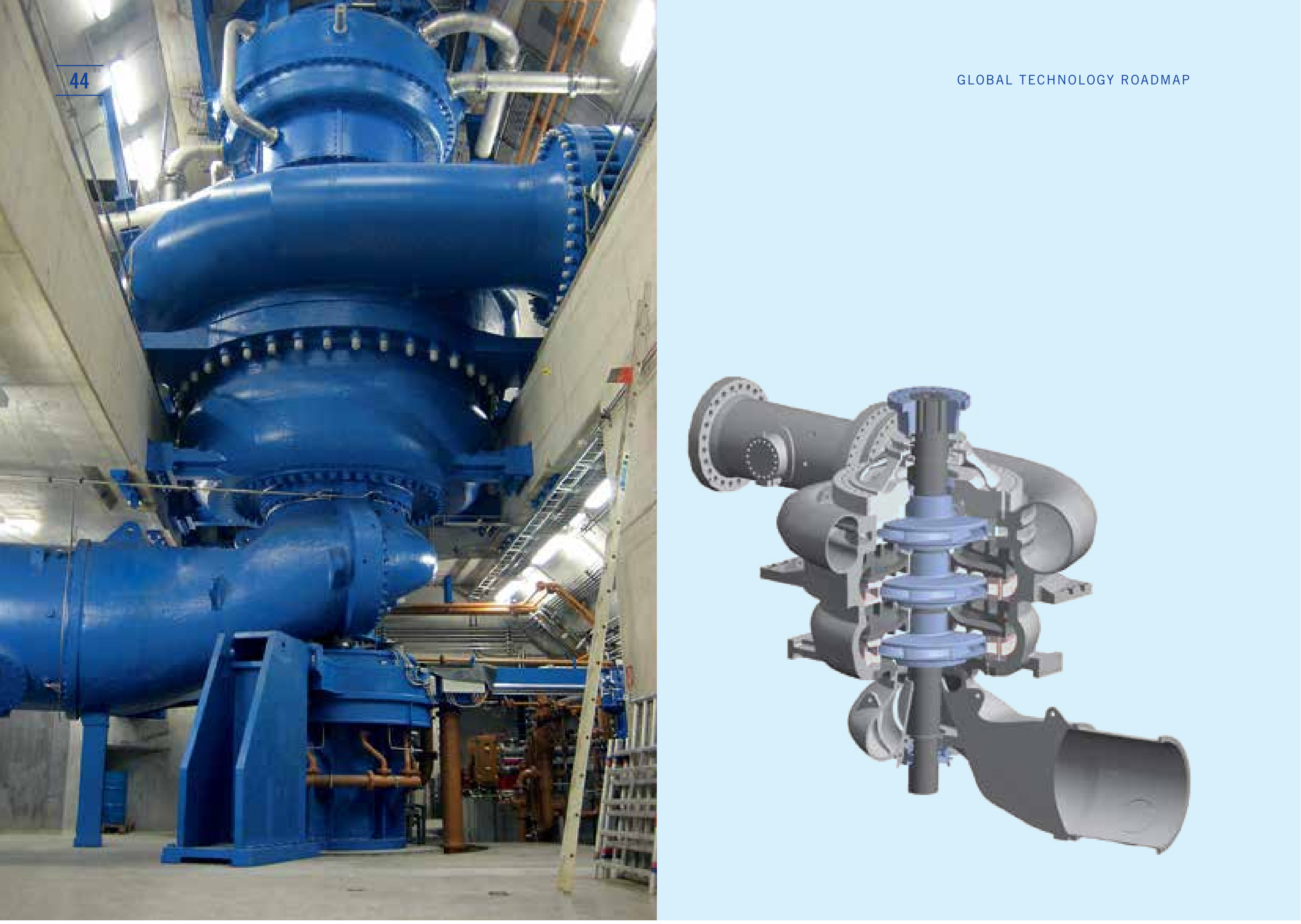


Figure 33: The Kops II multi-stage ternary pump-turbine (Austria)

Technology outlook

PSP will need to start and stop more often and faster. By 2030, the target is to have increased the lifetime of turbine runners and critical rotor parts from 10,000 stop-starts to 100,000.

The use of variable-speed technology supports this trend. Variable-speed technologies come in two flavors: the **D**ouble **F**ed **I**nduction **M**otor-generator (DFIM) and the **S**ynchronous **M**otor-generator with **F**ull-power **C**onverter (SMFC). The costs of SMFC are coming down, increasing its viability at high capacities.

Concerning the performance of power converter technology, the hydro equipment industry expects 20 kV converters to be available 'off-the-shelf' by 2020 and their size to have reduced from 2-3 m^3/MVA to 1.5-2 m^3/MVA. Current space requirements total about 5-6 m^3/MVA once cooling, filtering and access has been taken into account. Reductions are possible here, too. Efficiency will increase from 98% today to 99% by 2030.

Novel forms of PSP, some of them facilitated by variable-speed technology, are under consideration. These include:

- PSP built in or along the sea and that use the sea as a reservoir (to be situated close to wind farms and minimize offshore grid extension costs)
- PSP using underground reservoirs (such as disused mines)
- PSP using heavy masses (lifting a body of water on top of which rests a denser material, like sand).

By 2030 the industry wants to have demonstrated novel pumped storage technologies at 100-500 MW-scale, having first tested them at a scale of up to 20 MW.

Tools for sustainability measurement

THE HYDROPOWER SUSTAINABILITY ASSESSMENT PROTOCOL

The Hydropower Sustainability Assessment Protocol was launched in 2011. It is a framework for assessing hydro projects against around twenty social, environmental, technical and economic considerations, built by a diverse group of stakeholders including representatives from governments, commercial and development banks, social and environmental NGOs, and the hydropower sector. The Protocol can be used at any stage of hydropower development, from the earliest planning stages to operation. Since its launch in 2011, more than 20 projects of very different sizes (3–4,000 MW) have been assessed on all continents.

Assessments are based on objective evidence and are conducted by independent accredited assessors. The results are presented in a standardized way, making it easy to see how existing facilities are performing and how new projects are being developed.

The Protocol is valuable for:

- > Guiding sustainability issues and identifying gaps
- > Facilitating communication with stakeholders
- > Reducing the risk of investment opportunities
- > Enabling access to finance.

In 2012, the Hydro Equipment Association entered into a partnership with the International Hydropower Association (IHA) by which its member companies and some chosen stakeholders were trained in the use of the Protocol allowing them to understand better and improve the mastering of the tool.

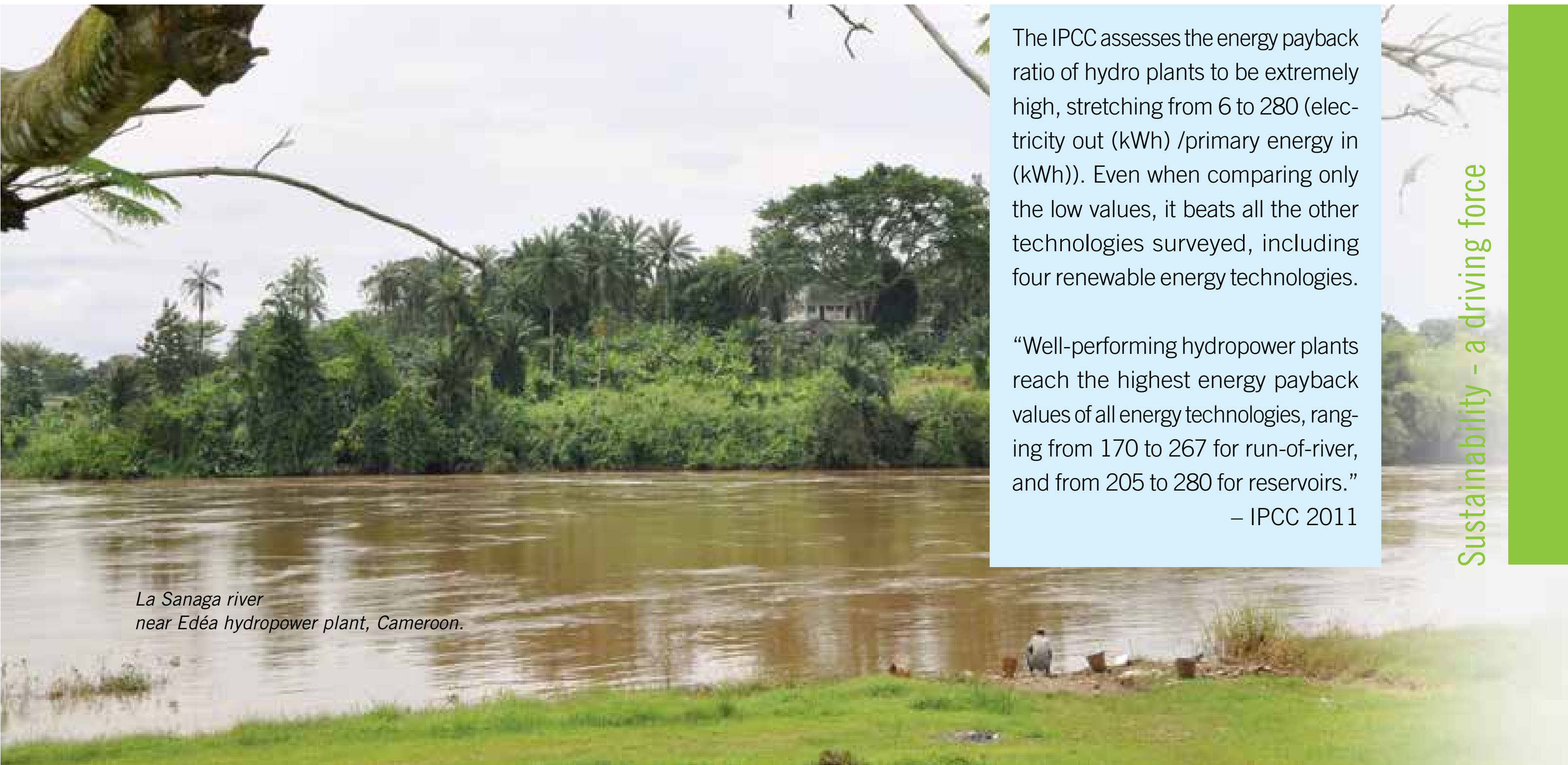
The main focus of HEA's sustainability efforts is on encouraging uptake of the Protocol and encouraging its recognition as an accepted hydro specific assessment tool. HEA and its members can play a key role here. Use and recognition of the Protocol by external organizations is increasing, including the OECD [OECD 2012].

LIFE CYCLE ASSESSMENT

Some manufacturers are going further by seeking to gather data linked to the sustainability profile of their components. With life cycle assessments, calculations can be made of the greenhouse gas emissions and other environmental impacts created in the manufacture of the product. It requires knowledge of the material and energy inputs of every component and subcomponent used in manufacturing. Some hydro equipment customers now demand such detail – the first approach coming in 2011.

The IPCC assesses the energy payback ratio of hydro plants to be extremely high, stretching from 6 to 280 (electricity out (kWh) /primary energy in (kWh)). Even when comparing only the low values, it beats all the other technologies surveyed, including four renewable energy technologies.

"Well-performing hydropower plants reach the highest energy payback values of all energy technologies, ranging from 170 to 267 for run-of-river, and from 205 to 280 for reservoirs."
– IPCC 2011



La Sanaga river near Edéa hydropower plant, Cameroon.

Environment-friendly equipment

ECOSYSTEM SENSITIVITY

Fish-friendly turbine variants of the Kaplan turbine

Water flows at lower velocities through such turbines, with less shear, fewer rapid pressure changes and less extreme absolute pressure levels, all of which help fish survival. In addition, to reduce the risk that fish get trapped or pinched in the gaps at the inner and outer blade peripheries (Figure 34 a and b), Kaplan runners with adjustable blades ('minimum gap runners' or MGR) have been developed. Examples of plants using them include the Bonneville Dam, USA (ten 7.1 m diameter runners commissioned between 1999 and 2010) and the Wanapum Dam, USA (ten 7.8 m diameter runners installed from 1995 to 2013). They offer fish survival rates in excess of 95% and higher efficiency over a large part of the operating range.

Figure 34 a: Minimum gap runner Kaplan turbines increase fish survival rates by making the gaps between blade and hub and blade and periphery as small as possible. Compare image on the left (minimal gap of trailing blade edge) with that on the right (wider gap).

Figure 34 b: The minimum gap runner viewed from an angle revealing its spherical turbine head (a design feature that increases fish survival).

Fish-friendly variants of the Francis turbine

The ‘Alden turbine’ (Figure 35) is a radial-flow turbine specifically designed for optimal fish-friendliness. The efficiencies of Alden turbines have been improved by 6% since 2008.

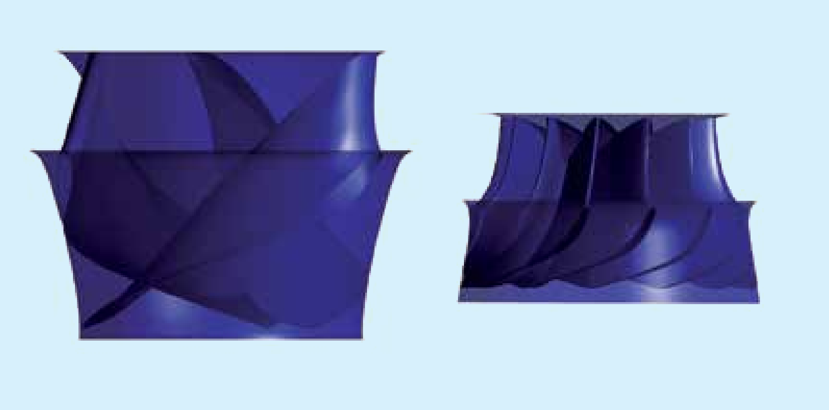


Figure 35: Images showing the Alden runner geometry (left) and a 13-bladed conventional Francis runner (right image) sized for the same head and flow.

AERATION OF WATER

The water at the bottom of many reservoirs contains low quantities of oxygen. This is also the part of the reservoir from which water is drawn to generate electricity in hydro projects.

The Auto-Venting Turbine has been developed to aerate the water as it passes through the turbine and mitigate the harm that oxygen-poor water can do to ecosystems downstream of the plant. Large amounts of air may be distributed as a stream of bubbles by feeding air though a hollow portion of specially engineered runner blades. This is a cost-effective solution for achieving environment-friendly operation while maintaining turbine efficiency.

OIL FREE OPERATION

Today, “oil-free” refers to the avoidance of oil and grease in those parts of the turbine in contact with water. It is already possible to eliminate oil completely from the design of Francis turbines. The elimination of oil from a Kaplan turbine is also feasible but more challenging, as in addition to removing oil from the governor and bearings, it must be removed from the hub. Hubs that avoid the need for oil have been deployed in several hundred projects, the largest of which is at Xayaburi, Laos, where seven vertical Kaplan runners each with a maximum power of 182 MW and diameter of 8.6 m will be installed. The last remaining step - oil elimination from the Kaplan runner governor - is in a conceptual stage. (Box 8 – technologies to reduce rather than eliminate oil use here are being trialled as well).

As a transitional measure, biodegradable non toxic oils satisfying the European eco-label are available to minimize water pollution from conventional turbine designs.

Roncovalgrande is a 1 GW Pelton turbine plant in northern Italy refurbished in 2012 for greater reliability. The grease that once lubricated the 44 Pelton injectors was replaced by a self-lubricating system. The loss of oil from the hydraulic regulation mechanism was significantly reduced and energy savings were achieved from the use of overlapped proportional valves. The remaining lubrication need is met with biodegradable oil.

Replacing a low-pressure governor system with a high pressure system reduces the amount of oil needed, hence the amount that can leak into the environment.

Complete elimination of oil from the governor system has been demonstrated for a Francis turbine at the Porjus Unit 8 project, Sweden.

Box 8: Refurbishments for oil reduction / elimination

Improved infrastructure

CIVIL WORKS

Solutions based on civil works, especially if undertaken after plant construction, are expensive and the reduction in the net head of water is of the order of 3-4%, impacting energy generation.

They are, however, among the traditional approaches to improving fish friendliness. A channel bypassing the turbine may be built from the top of the reservoir to the downstream watercourse. At the intakes to the turbines, fish diversion screens may be installed to guide fish down a passage that continues to the tailrace. Upstream fish migration can only be aided with civil works (Figure 36). A detailed discussion is beyond the scope of this paper and the domain of hydro equipment.

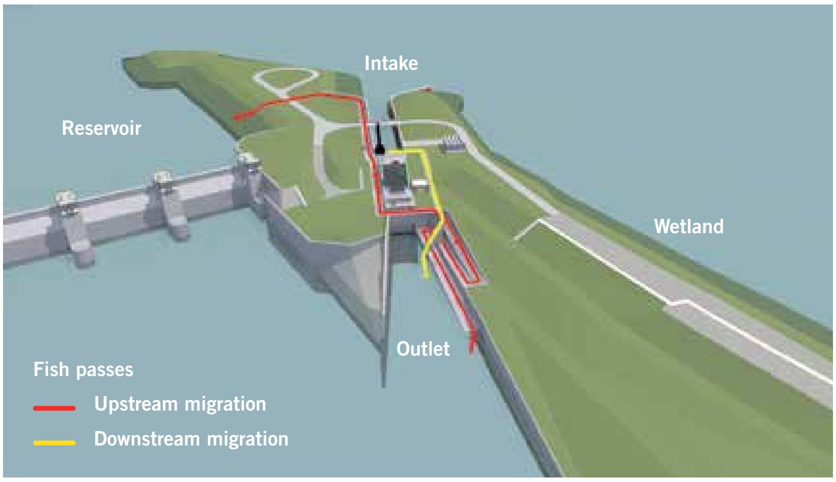


Figure 36: Diagram of Rochemaure small hydropower plant. The upstream passage consists of 50 pools, the downstream passage (designed with the needs of eels in mind) of a 190 m^2 fine screen (2 cm gap between bars) at an angle of 20° to the flow. The screen guides the fish up to the passage entrance without crushing them against the flow. The plant (both its power generation and fish passage parts) was designed by CNR, which also supplied this picture.

APPEARANCE OF PLANTS

Plant appearance, land use and reservoir size are unaffected by refurbishment work (Figure 37).

Figure 37: Spot the difference? The Bajina Bašta plant in Serbia was upgraded in the five years 2008-2012 from 4x 95.4 MW turbines to 4x 105.6 MW, increasing output by 13% (=40 GWh additional generation per year) without changing the plant's appearance.

Technology outlook

Fish survival

> Continued investigation of fish mortality causes

Recent biological investigations involving shear, strike, and minimum pressures have provided valuable insight into turbine design criteria. Continued investigation into fish mortality factors that are present during hydro turbine passage is critical for establishing the appropriate design guidelines for hydro turbine equipment. Extension of these studies to a larger range of fish species will also expand the range of fish passage applications.

> Increased use of computational tools to improve fish passage characteristics for hydro turbines

Integrating biological considerations with computational results is necessary for optimal environmental design. Post-processing tools are being developed to make the connection between computed flow fields and fish mortality. The results of these tools are being used to refine turbine geometries. In the future, these tools will be more sophisticated and their application will be more widespread.

> Biological testing on prototype turbine installations

Recently commissioned projects provide an excellent opportunity to collect information on actual fish passage. Such data may be reused in design methodologies and prediction tools.

> Demonstration of the Alden Turbine

The Alden turbine design is expected to improve direct turbine survival rates for smaller radial flow applications where blade strike is a leading contribution to mortality. Installation of a prototype Alden turbine will provide valuable correlations for fish survival rates, operational characteristics project schedule and costs. The current Alden turbine design is suitable for a rather narrow range of head and flow applications. Future development is expected to expand this application range, increasing the number of potential sites.

> Increased use of the minimum gap runner or concepts that achieve similar results

The next generation of fish passage technology for axial flow turbines will integrate the Minimum Gap Runner concept with new biological design criteria.

Materials and substances

> By 2030 it will be possible to avoid oil and grease altogether in all parts of the turbine. Scandinavia is the leading market for oil-free designs, followed by Scotland and Central Europe. Demand is growing elsewhere.

> In manufacturing, potentially toxic materials (e.g. anhydrides) are continuously checked and replaced with better alternatives.

Abbreviations and glossary

- **ENTSO-E**: Association gathering all European Network Transmission System Operators for Electricity
- **EU:** European Union
- **EUR:** Euro
- **GDP:** Gross Domestic Product
- **GHG:** Greenhouse gas
- **GWh:** Gigawatt hour
- **HEA:** Hydro Equipment Association
- **IEA:** International Energy Agency
- **IHA:** International Hydropower Association
- **IPCC:** Intergovernmental Panel on Climate Change
- **IRENA:** International Renewable Energy Agency
- **kV:** Kilovolt
- **MVA:** Mega volt-ampere
- **MWh:** Megawatt hour
- **OECD:** Organisation for Economic Co-operation and Development
- **Penstock:** Pipe carrying water to the turbine
- **PSP:** Pumped hydro storage plant
- **PV:** Photovoltaics
- **Radial-flow turbine:** Turbine type where water enters the turbine from the edge of the runner (i.e.in the plane of rotation), as distinct from 'axial-flow turbines', where water enters the turbine above the runner (i.e. perpendicular to the plane of rotation)
- **REN 21:** Renewable Energy Policy Network for the 21st Century
- **Spinning reserve:** Rotating generators that are online supplying power but still able to increase their power supply following grid needs in short notice (typically within tenth of seconds)
- **Synchronous rotating generator:** A generator that rotates at a fixed speed which is a fraction of the electricity grid frequency (50 Hz in Europe)
- **Tailrace:** The race, flume or channel leading water away from the hydropower plant
- **USD:** US dollar
- **Variable-speed:** Describes turbines or pumps that drive generators (or are driven by motors) that are able to regulate their rotation speed over a range different from a fraction of the electricity grid frequency
- **WB:** World Bank

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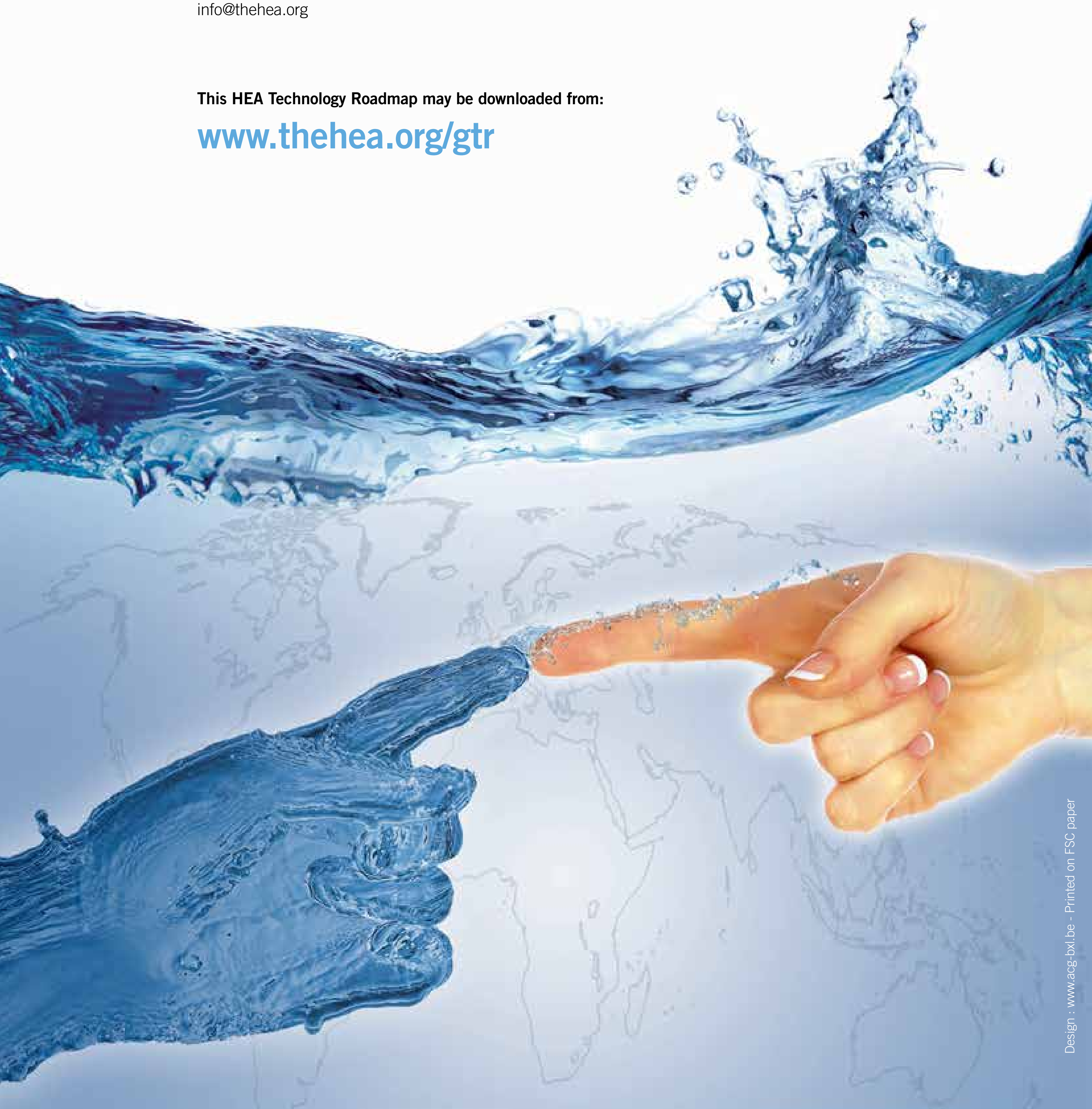

Design : www.acg-bxl.be - Printed on FSC paper