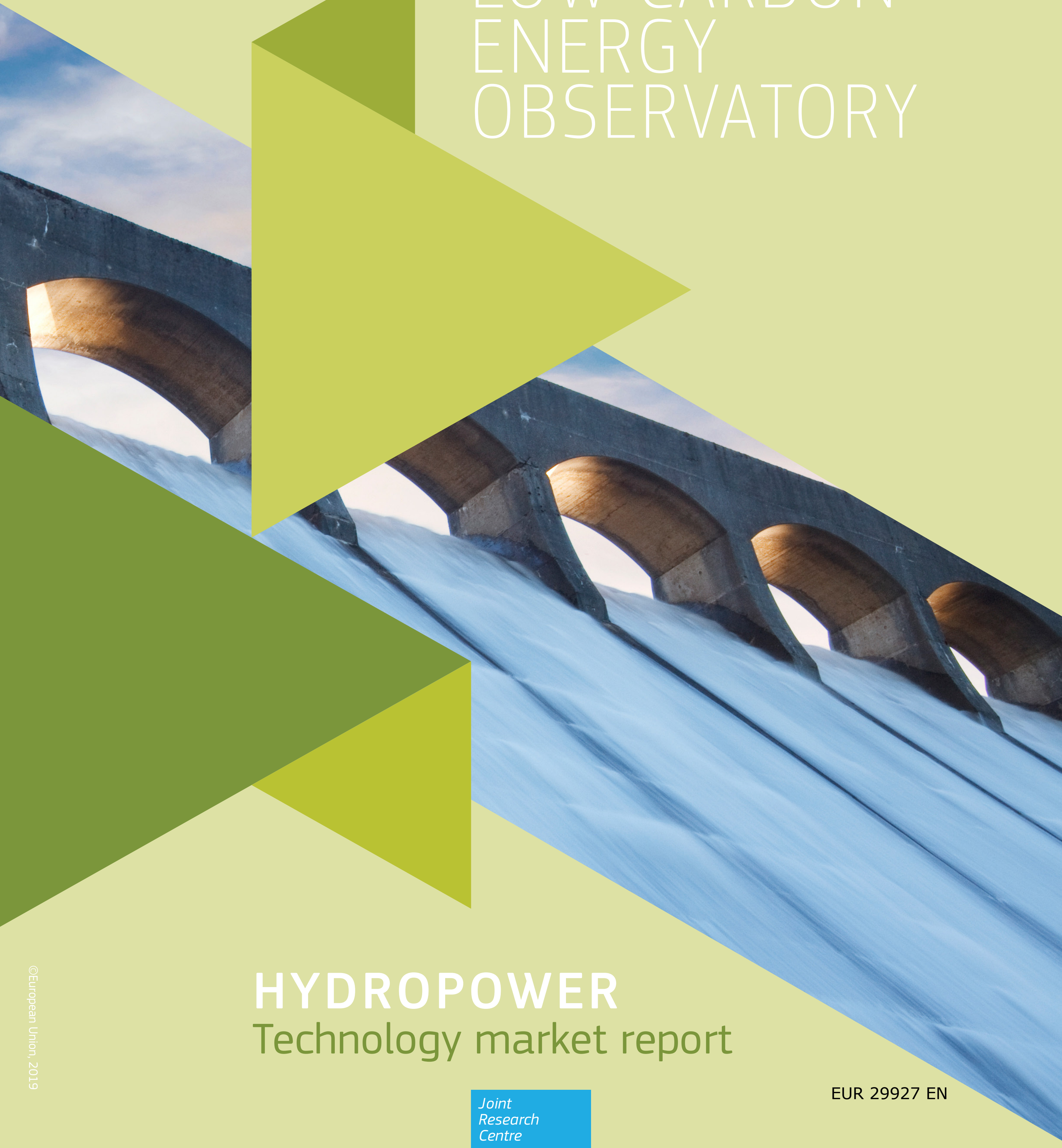
European Commission

LOW CARBON ENERGY OBSERVATORY



HYDROPOWER
Technology market report

EUR 29927 EN

Joint Research Centre

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Foreword on the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind Energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon Capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?
JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?
The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports?
Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

Executive summary

The present report outlines the current market status and recent developments of the hydropower sector in the EU but also extends its scope at the global scale. Hydropower has provided clean electricity for more than a century and its importance for the power systems is shown by the fact that, globally, $\simeq$160 countries use hydropower for energy production. Hydropower is crucial for system stability and security of supply and it supports the integration of large capacities of variable renewable energy sources (RES). Since the EU relies to a large extent on energy imports, hydro being a domestic source strengthens energy security and independence.

The report offers an insight into the European Union's hydro fleet —status and developments— also analysing its productivity and role in national power portfolios. This includes a presentation of recently completed and ongoing installations in the EU. It also analyses the particular case of pumped hydropower storage stations and their utilisation trends in the EU. The particular case of the Western Balkan countries is analysed, a result of the increased interest in developing the significant untapped sustainable hydropower sources in the region.

Aiming at interpreting the market trends and the influencing factors, the report provides the status of hydropower's industry. Besides, hydropower is an important EU export business with the worldwide market penetration exceeding 50%. The analysis included a thorough study of the latest financial reports of leading components' manufacturing companies. Public and private investment in hydro research and development (R&D) has also been analysed, covering the period from the early 2000s until recently. This was coupled with a detailed patent analysis that has global coverage and is based on a JRC in-house developed methodology. In that way, the report provides an EU outlook of hydro activity with a global perspective.

Modelled projections on the future role and development of hydropower in the European Union are also provided. Using the JRC-EU-TIMES model, we processed a wide range of input parameters and ran different scenarios in an attempt to anticipate future installations of the different types of hydro stations as well as additions and upgrades in the existing fleet. The economics of technology and the existing barriers to further market expansion are also discussed.

1 Introduction: Hydropower status and development

1.1 Global status

The cumulative global power capacity of hydropower reached 1267 GW at the end of 2017 including pumped hydropower storage (PHS) stations. The produced electricity was 4184 TWh (IHA, 2018). The RES statistics provided by the International Renewable Energy Agency (IRENA) are slightly more optimistic and estimate the total installed hydro at 1270 GW (IRENA, 2018b). Worldwide, investments of more than EUR 42 billion were committed to hydropower development resulting in additions of 21.9 GW of hydropower capacity in 2017, a moderate increase compared to the previous years. According to (Bloomberg New Energy Finance, 2018a), 19 GW of large-scale hydropower (LHP) and 2.9 GW of small-scale hydropower (SHP) (1–50 MW) were added in 2017.

Considering the global hydropower capacity of 1105 GW at the end of 2012 (including PHS), the average annual global additions in the past five years were 32.4 GW/year. Over the last decade, 34.4 GW of hydro were added on average every year, equivalent to a compound annual growth rate (CAGR) of 3.16%.

Hydropower also provides off-grid electrification services representing 7.75% of the currently installed distributed electrification capacity. Overall, an additional 509 MW off-grid hydro is installed worldwide; mainly in Africa (31.8%), S. America (30.3%) and Asia (25.0%). Over the past decade, the CAGR of off-grid hydro was 2.35%.

East Asia and Pacific regions host a significant part of the global hydro capacities ($\simeq$37%). Europe hosts approximately 1/5 of the world's hydro capacity and North America an additional 16.5%. South America with 166 GW and South-Central Asia with 144.7 GW host notable hydro capacities. Africa hosts only 3% of the global hydropower capacity and it is the continent with the lowest utilisation of the existing hydro potential. Figure 1 shows the installed hydro (conventional and pumped hydropower storage (PHS)) per geographic region.

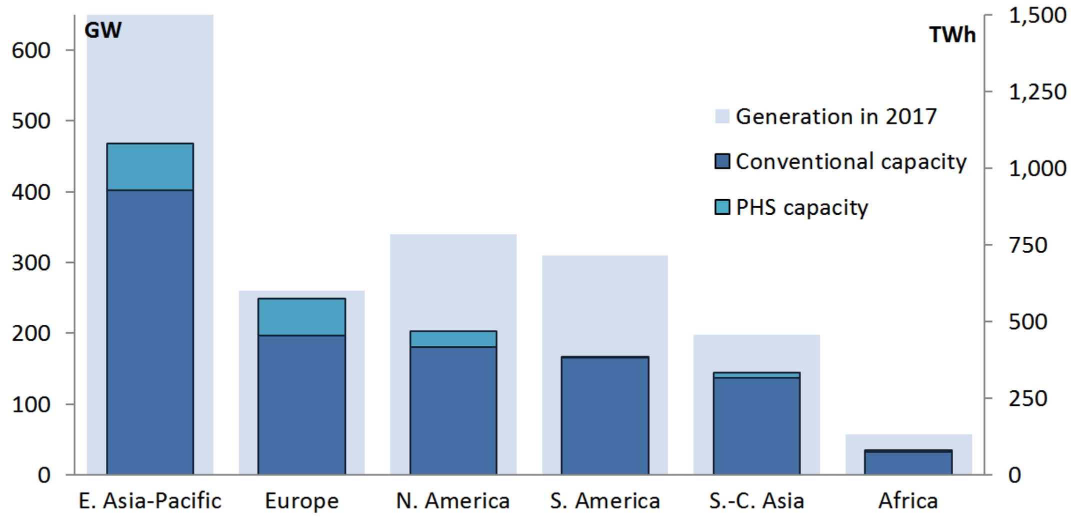

Figure 1: Global installed hydro capacity of conventional and PHS stations (GW) and their electricity production in 2017 (TWh). Source: Author's compilation on International Hydropower Association (IHA) data (IHA, 2018)

Country-wise, the global leader is China with an installed hydropower capacity of 341.2 GW, 28.5 GW of which is PHS. Between 2008 and 2017, the hydro sector of China grew at an impressive CAGR of 7.87%. United States (US) is ranked second with 102.8 GW (22.8 GW of which PHS), followed by Brazil (100.3 GW, of which a negligible 30 MW PHS), and Canada (81 GW). The countries with the highest installed hydropower capacity are presented in Figure 2 along with the value for EU. The background light blue columns of Figure 2 illustrate the 2017 electricity generation (right axis).

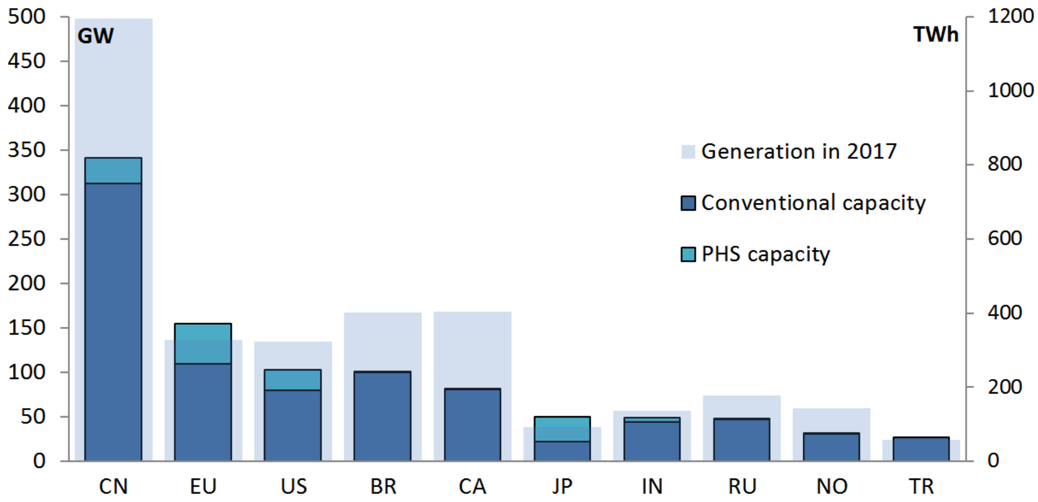

Figure 2: Installed hydro capacity (GW) and production (TWh) in the main countries (end of 2017). Source: Author's compilation of IHA data (IHA, 2018)

1.2 EU hydropower fleet and production

As of late 2017, the total installed hydro in EU was ≃155 GW, 1 GW higher than the previous year. In July 2019, Eurostat published the latest information regarding EU's installed hydro. According to that, EU's cumulative hydropower capacity in late 2017 (Eurostat, 2019) was 155.12 GW, 48.51 GW of which PHS. This report also analysed 2017 data provided by the IHA and IRENA. IHA reported a cumulative power capacity of 154.48 GW (including 44.97 GW of PHS), while IRENA's estimation is 155.17 GW. The 2016 Eurostat data (Eurostat, 2018) reported total EU installations of 153.97 GW, 47.91 GW of which is PHS (Figure 3). The largest part of the stations' total capacity (91.8 GW) is hosted at LHP stations with a nominal power capacity exceeding 10 MW, while a total 10.7 GW is SHP (1–10 MW) and the remaining 3.6 GW refers to mini-scale projects (<1 MW). Autonomous producers operate ≃1.9 GW. Figure 3 shows the 1990–2016 timeline[1] of installed hydro in the EU.

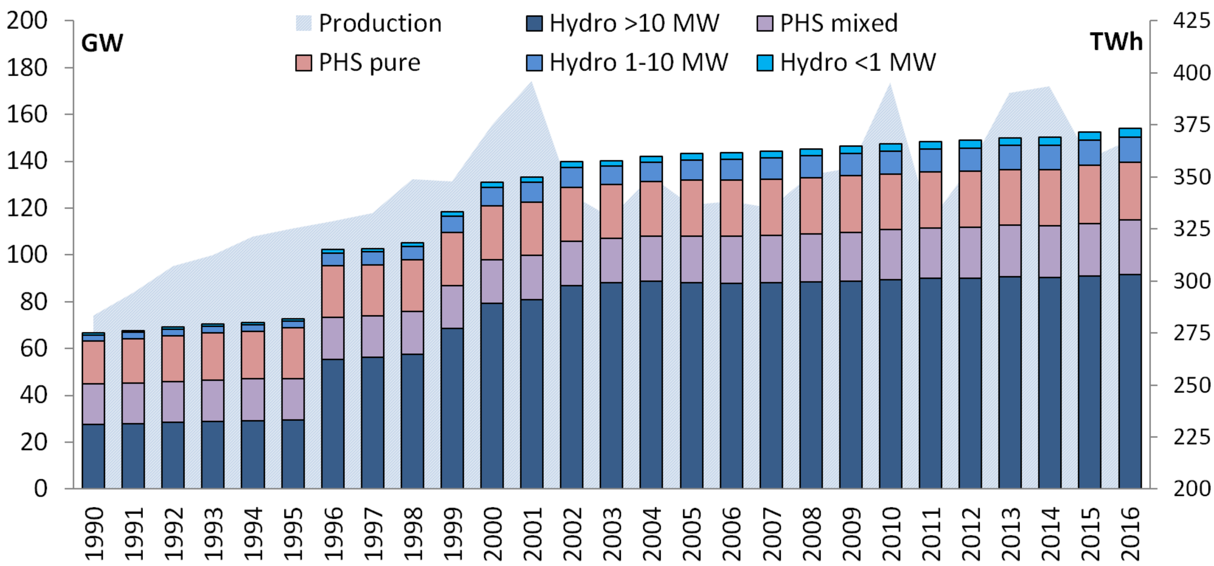

Figure 3: Installed hydropower capacity (GW) in the EU and annual net hydroelectric production (TWh) (1990–2016). Source: Author's compilation of Eurostat data (Eurostat, 2016, Eurostat, 2018)

[1] The 2019 Eurostat release adopts different categorisation for hydro. SHP and mini-hydro are not reported and, instead, the categories are reservoir hydro, run-of-the-river (RoR), pure and mixed PHS.

The light blue background area in Figure 3 shows the annual hydroelectric output (net) in the EU. The values, shown in the right-side axis in TWh, reveal the seasonal variability of hydropower production: In the last twenty years (1996–2016), and despite capacity additions, the annual output oscillates between $\simeq$335 and 400 TWh/year with the average value being 360 TWh/year. New hydropower development in EU has been very moderate after 2000. The CAGR for 2000–2016 was equal to 1%, while for 1990-2000 it was equal to 7% (total capacity grew from 66.6 GW to 131.2 GW). Overall, for the period 1990–2016, hydro's CAGR has been 3.27%. An important reason for this deceleration is the introduction of the Water Framework Directive 2000/60/EC (WFD) in 2000 that aims to preserve the ecological status of European surface waters (European Parliament, 2000). Thus, measures to protect the environment and river ecology set a barrier in new dam construction.

The map of Figure 4 shows the installed hydro capacity in each EU member state (MS). It distinguishes six classes of countries, depending on the total installed power. Pie charts show the share of PHS (mixed and pure), LHP, SHP and mini-hydro per country. Notably, certain MSs with significant capacities (Sweden, Romania, Finland) host negligible PHS. In these cases, conventional reservoir LHP stations provide instead the required flexibility.

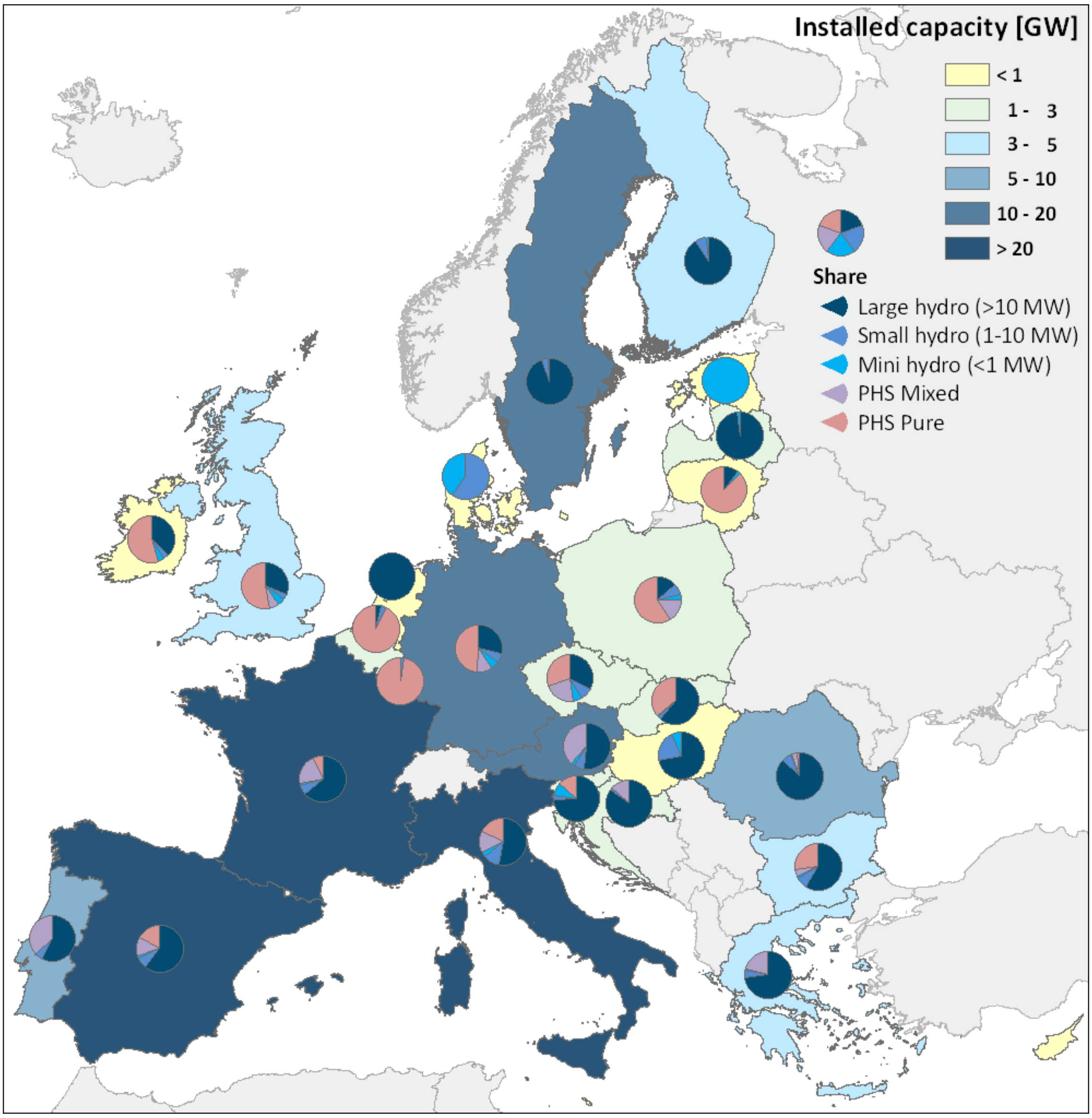

Figure 4: Installed hydropower capacity (GW) in EU member states (2016) and its distribution in the different types of stations. Source: K. Bódis' compilation of Eurostat data (Eurostat, 2018)

Figure 5 shows the installed hydropower capacities in every EU member state at the end of 2016 (Eurostat, 2018). Information is broken down per technology type. The light blue background columns show the 2016 net hydroelectric output per MS (TWh, right axis).

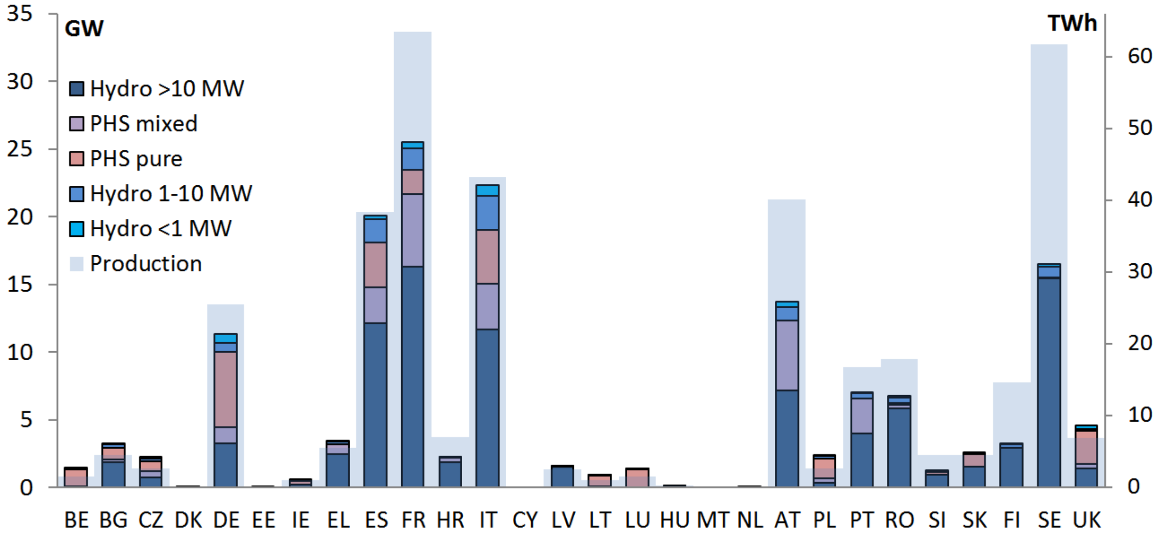

Figure 5: Installed hydropower capacity (GW) and total annual net hydroelectric production per EU member state (2016). Source: Author's compilation of Eurostat data (Eurostat, 2018)

The share of hydropower net electricity generation in the net electricity production was 11.9% for the whole EU in 2016. The share of hydros' output varied between 10.4% and 13.4% in the period 1990–2016 as it also depends on the hydrologic year. EU's share is generally below the global average; hydropower contributed 17% of the global electricity generation in 2017 with a production of 4,184 TWh out of the total 24,656 TWh (IHA, 2018).

Figure 6 shows the share of hydropower (including PHS) in each MS's total net electricity production. It illustrates the annual minimum, maximum and average values over an analysed period spanning between 1990 and 2016. The MSs with large values of installed capacity (Austria, Sweden) produce large parts of their electricity from hydro. Several MSs also produce a high share of consumption in their hydro stations, mainly the result of relatively lower consumption figures. In 2016, Austria produced ≃62% of its electricity at its hydro stations, Sweden 40.5%, Croatia 56.7%, Latvia 42.5%, and Luxembourg 69.7%.

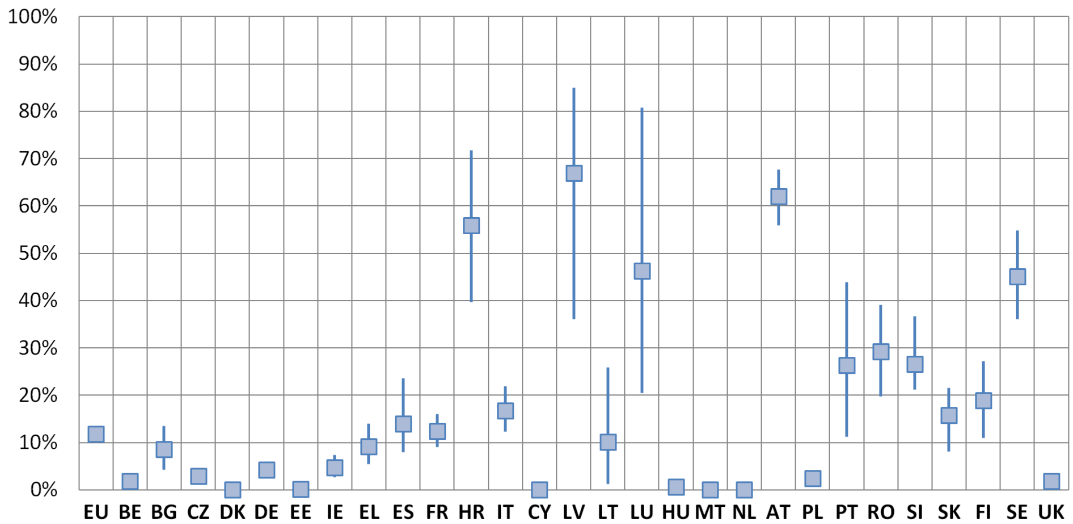

Figure 6: Share of net electricity generated by hydro in the total net production in the EU member states (1990–2016). Source: Author's compilation of Eurostat data (Eurostat, 2016)

Annual capacity factors of hydropower in EU

There is a difference in the productivity of hydropower stations across Europe. This is due to climatic conditions (i.e. precipitation, hydrology) and the geomorphology (hydraulic head) that defines the technical characteristics of each station. In certain EU regions, water inflows into hydropower reservoirs are abundant for longer periods throughout the year and so are the river water discharges that power RoR hydroelectric projects. It is obvious that such conditions favour hydroelectric productivity as they allow hydro stations to operate near their nominal capacity for longer periods of time. Annual changes are also observed within countries and are dictated by the different year-to-year climatologic conditions (high or low precipitation year).

Figure 7 shows the yearly average capacity factors of the hydro fleet of each MS. Values include mini-scale, SHP and LHP but not PHS stations. Pure PHS are net consumers of electricity; therefore, the capacity factor (CF) index is not commonly used when analysing the productivity of storage stations. Hydropower productivity in Cyprus and Malta is zero, because these countries do not host any hydro capacity.

Hydro stations in central-north EU have higher productivity, shown by their relatively higher CF. LHPs in Austria and Germany have an average CFs that exceeds 55%, while in several MS the LHPs average productivity is ≃40–50% (e.g. Finland, Sweden, Croatia). Large-scale stations in France and Italy have average CF 34%–37%, while the countries of South Europe experience lower productivity; LHPs' capacity factor in Portugal, Spain, Greece and Bulgaria is—on average—between 20% and 30%. Overall, the CF of large hydros in EU is 37.1%, with this value slightly decreasing for the smaller stations (35.5%). Detailed tables for the CF over the analysed period are provided in the Appendix (Tables 6–8).

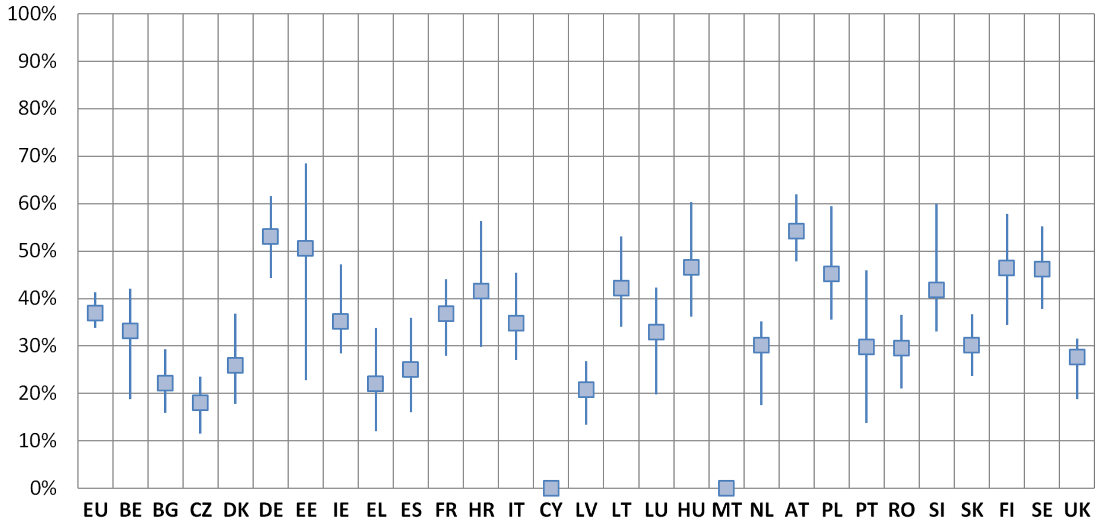

Figure 7: Capacity factors of hydropower stations operating in EU member states. Average, minimum and maximum values for 2000–2016. Source: Author's compilation of Eurostat data (Eurostat, 2016)

Multiple uses of hydro projects may also play a (minor) role. Certain hydroelectric projects are designed and operated to serve more than one purpose such as water supply, irrigation, navigation and others. In such projects, a working plan is devised to design the required compromises to make the different uses as much compatible as possible with one another (Linsley and Franzini, 1979). Constant or seasonal water requirements for other uses affect electricity production. According to the GRanD v1.3 database (Lehner et al., 2011), multipurpose schemes are not common in some of the countries with high hydropower productivity (Austria, Sweden, Finland). On the contrary, a number of multi-purpose schemes operates in countries where hydropower stations produce at relatively lower CFs (Czech Republic, Spain, Greece). However, this observation does not have general applicability as several exemptions can be detected (e.g. Germany).

1.3 National Renewable Energy Action Plans

According to the 2009/28/EC Directive, the MSs needed to adopt a National Renewable Energy Action Plan (NREAP) that describes their future planning for the share of renewable energy sources in gross final energy consumption in the reference year 2020. The publication of the first recast of the Renewable Energy Directive in late 2018 was coupled by an update of the EU rules on the governance of the energy union and climate action. EU member states are, thus, required to develop integrated National Energy and Climate Plans (NECPs) for the period 2021–2030.

The present report analyses the progress in reaching the NREAP planning. Table 1 shows the planned and achieved installed capacity and electricity production of hydropower. In general, this includes the output of mini-scale, SHP, LHP and mixed PHS. However, MSs indicated their planning in a not fully-consistent manner as far as pumped hydropower storage power capacities are concerned. This particularity, was underlined in the previous series of the EC Joint Research Centre (JRC) hydropower market report (Kougias, 2016b), and is also mentioned in the relevant NREAP document (Beurskens, L.W.M. and Hekkenberg, M., 2011). Accordingly, two MSs (France and Spain) include both mixed and pure PHS in their target capacities. The present analysis takes this inconsistency into account and analyses the data accordingly. It is worth mentioning that three MSs (Czech Republic, Germany and Austria) had not included any PHS capacities in their future planning.

Table 1: Hydropower in the EU: NREAP planning and progress.

	Power capacity (MW)	Electricity production (GWh)
2005 baseline	117076	346641
2010 actual	121395	401122
2010 plan	120019	345747
2015 actual	125672	364852
2015 plan	127687	361700
2016 actual	127290	373688
2020 plan	138010	376789

Source: (Eurostat, 2018, Beurskens, L.W.M. and Hekkenberg, M., 2011)

According to Table 1, the interim EU-wide planning for 2010 was over-achieved, while that of 2015 was almost reached. However, and considering the progress from 2010 and on ($<$1 GW/year), the 2020 plan of 138 GW hydropower in EU as indicated in the NREAPs will not be reached.

EU member states have included hydropower development in their NREAPs with the country-level targets presented in the left side of Table 2 (apart from Malta and Cyprus). In the right side of Table 2, the actual hydropower capacities are presented. The 2016 deployment is 2.25% lower compared to the 2016 projection and at about 92.2% of the 2020 EU target. In total, another 10.7 GW of hydropower need to be installed in EU in the 2016–2020 period in order to reach the target.

According to the 2016 data of Table 2, certain countries were lagging behind their original planning. This includes Greece (need to install $>$1.1 GW in 2016–2020), Spain ($>$2 GW), France ($\simeq$2.8 GW) and Portugal ($\simeq$2 GW). The latest completed developments, however, show post-2016 activity that has not yet been reported by Eurostat. This activity shows some progress that may partly bridge the gap with the 2020 planning. A typical example is the completed and ongoing large-scale projects in Portugal.

Table 2: Hydropower capacity in EU: NREAP planning and progress (MW)

	Planned NREAP power capacity				Actual power capacity			
	2005	**2010**	**2015**	**2020**	**2005**	**2010**	**2015**	**2016**
BE	108.2	112.3	122.5	140	105	118	112	115
BG	2078	2090	2280	2549	1984	2184	2355	2359
CZ	1020	1047	1099	1125	1020	1049	1088	1090
DK	10	10	10	10	11	9	7	10
DE	4329	4052	4165	4309	4134	4252	4577	4573
EE	5	7	8	8	5	6	6	6
IE	234	234	234	234	234	237	237	237
EL	3107	3237	3615	4531	3106	3215	3392	3392
ES	18220	18687	20049	22362	18220	18535	20053	20056
FR	25349	25800	27050	28300	25130	25425	25299	25517
HR	2082.7	2139.2	2167.1	2456	2060	2141	2208	2205
IT	15466	16580	17190	17800	17036	17563	18238	18316
CY	0	0	0	0	0	0	0	0
LV	1536	1536	1550	1550	1536	1576	1589	1565
LT	128	127	133	141	117	116	117	117
LU	34	38	38	44	34	34	34	34
HU	49	51	52	66	49	53	57	57
MT	0	0	0	0	0	0	0	0
NL	37	47	68	203	37	37	37	37
AT	7907	8235	8423	8997	7667	7913	8120	8458
PL	915	952	1002	1152	915	936	964	972
PT	4816	4898	7065	8940	5017	5106	6168	6960
RO	6289	6413	7287	7729	6289	6382	6638	6642
SI	981	1071	1193	1354	979	1074	1115	1113
SK	1597	1622	1732	1812	1596	1600	1606	1608
FI	3040	3050	3050	3100	3035	3155	3249	3250
SE	16345	16350	16355	16360	16345	16732	16329	16466
UK	1501	1710	1920	2130	1501	1947	2077	2135
EU	117076	119983	127735	137402	118162	121395	125672	127290

Source: National Renewable Energy Action Plan (NREAP) (Beurskens, L.W.M. and Hekkenberg, M., 2011,Ministry of Economy, 2013)

1.4 Utilisation of EU's pumped hydropower storage fleet

PHS is an important hydro sub-technology as it is the main means for bulk energy storage. The globally installed PHS capacity exceeds 153 GW and represents ≃99% of the available grid-scale electricity storage (Kougias and Szabó, 2017). Originally, PHS stations utilised and stored the minimum technical output of night production of coal-fired and nuclear power stations. With the surge in RES, a sustained interest in PHS has appeared, due to its technical characteristics that can potentially enable higher penetration of RES into power systems. A number of studies have, thus, analysed the important balancing role PHS could provide as the production of variable RES grows, especially in periods in which RES output is plentiful.

It is commonly assumed that PHS will be utilised at higher rates, nearer to its full extent and this will be coupled with construction of new PHS stations. However, there is evidence that the growth of PHS is not linearly related to the actual storage needs. Notably, a number of MSs has been decreasing the utilisation of their existing PHS fleet despite the increasing share of RES in their power systems (Kougias and Szabó, 2017). Figure 8 shows the cumulative electricity consumption in the EU PHS fleet over the last decade (2008–2018). It is shown that the amount of electricity consumed in the pumps of EU PHS stations and, thus, stored has not increased; on the contrary, the red trend-line in Figure 8 shows a slight decrease over the analysed period.

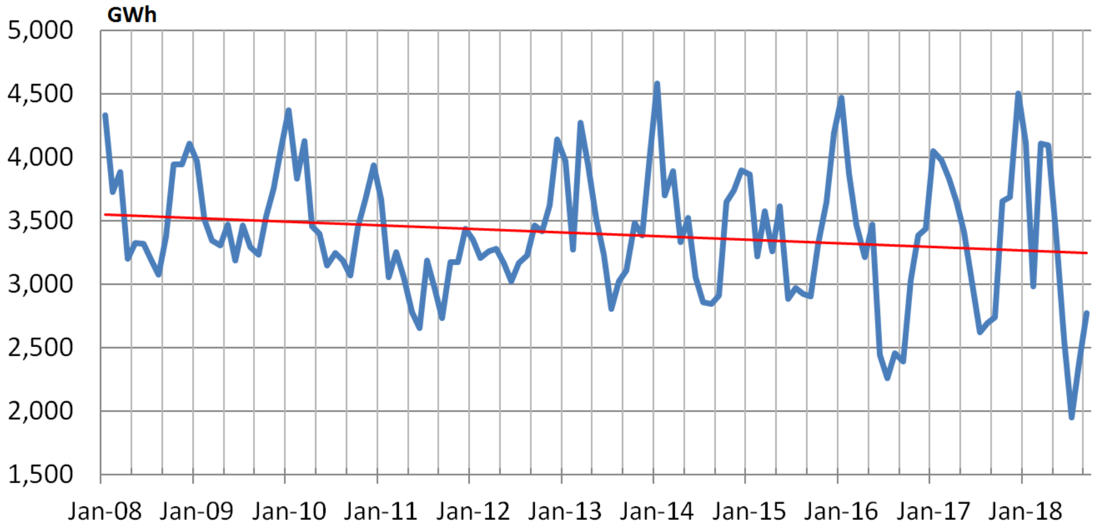

Figure 8: Electrical energy used for pumped storage in EU for 2008–2016 (blue) and trend (red). Source: Author's compilation on Eurostat data (Eurostat, 2016)

The detailed analysis conducted in (Kougias and Szabó, 2017) reveals that certain MSs have decreased the utilisation rate of their PHS fleet. In some cases, this was not counterbalanced by the addition of new storage stations. Such are the cases of Italy, Poland and Greece. Contrary to that, other MSs have increased the storage service of their PHS fleet. This is the case of Germany, Spain, France, Bulgaria and Czechia. Furthermore, there are several MSs where PHS utilisation rate has remained almost stable. Attempting to interpret this discrepancy, it appears that it is probably the result of a combination of influencing parameters that vary among MSs. An important driver are the market conditions that do not favour a growth of the storage market. Low wholesale electricity prices and market mechanisms not favourable to PHS stations have made their operation less profitable. In short, PHS stations are operated in high rates mainly in MSs with significant nuclear power capacities. The abundance of nuclear electricity production results in the required price difference that allows arbitrage purchases, a sine qua non for economically viable operation of PHS. Besides, nuclear operation has only little flexibility and, thus, storing excess nuclear production during periods of low consumption is important also for systems' stability.

In some countries, PHS stations are being imposed transmission fees when in pumping mode. In such cases, the consumed power is charged twice with grid utilisation fees, both when pumped/stored and when fed back into consumption points. This has a negative impact on the economic viability of the operation of PHS. It may, thus, result in the use of mixed PHS as conventional hydro stations that only utilise natural inflows.

An additional obstacle for the expansion of the PHS market is the competition with flexible conventional sources i.e. open cycle gas turbine (OCGT) and closed-cycle gas turbine (CCGT) technologies. Particularly in periods of relatively low prices of natural gas, it appears that power companies prioritise the operation of gas turbines to provide balancing services and peaking power. An additional driver resulted from a consultation with utility companies' associates: Utilities may prioritise gas turbines operation over PHS on corporate accounting ground. In the EU, the majority of PHS was built decades ago and the initial investments have been mostly recouped. Contrary to that is the high number of gas power stations developed in the post-2000 period where the capital recovery has not been yet reached.

1.5 Recently completed and ongoing projects in the EU

In 2017, 2.3 GW of hydropower capacities were added in Europe including non-EU countries. Out of that, ≃1 GW of new hydro became operational in EU member states. In the recent years, Portugal has been leading new hydropower deployment in EU. As also shown in Table 2, recent activity was concentrated in MSs that traditionally rely on hydroelectricity such as Austria, Sweden, France and Spain.

Portugal

In April 2017, the "Frades II" project started its operation, taking advantage of an existing dam (Venda Nova) and its 420 m hydraulic head with the downstream reservoir (Salamonde). The 780 MW project (1273 GWh gross annual production) is one of the largest PHS stations in EU equiped with variable speed turbines.

Portugal has announced its plans to develop three new dams and hydropower plants (one of which will be PHS) on the Tâmega and Torno rivers in northern Portugal with a total power capacity of 1158 MW. In July 2018, Iberdrola, the energy company that will construct the scheme, secured a EUR 650 million loan from the European Investment Bank (EIB), while the estimated total cost is EUR 1.5 billion. The three dams, "Alto Tâmega", "Daivões" and "Gouvães", are expected to produce ≃1760 GWh on an annual basis. The "Tâmega" hydropower scheme is expected to commence its commercial operations in 2023.

Romania

State-owned power utility Hidroelectrica currently operates hydropower plants with a total installed capacity of 6400 MW in Romania (≃95% of the total). Romania released its draft Energy Sector Strategy for the period 2018–2030 at the end of September 2018. It foresees investments worth EUR 800 million for modernising the existing hydropower fleet. It also envisages an additional EUR 2.5 billion for approximately 750 MW of new projects by 2030.

In terms of recently completed projects, in December 2017 and following an investment of EUR 58 million, the 12 MW "Bretea" project was inaugurated (IHA, 2018). Following a EUR 200 million investment made by Hidroelectrica, the 35 MW "Rastolnita" project is at an advanced stage.

The plans for Tarnita-Lapustesti PHS, although at an advanced stage, have been delayed due to the fact that the Energy Ministry questions its economic viability. Initially, the construction of Romania's first PHS station was originally planned to begin in 2017 and last between 5 and 7 years. A public-private partnership between Romania and a China-based group would finance the 1 GW project's investment estimated at EUR 1.3 billion (Năstase et al., 2017). Halting of the activity follows a draft bill prepared by Romania's Waters and Forests Ministry in late 2018 that envisages prohibiting the construction of new hydropower plants in Romania at altitudes between 800 m and 1500 m.

Switzerland

Switzerland, a country associated to EU, has traditionally relied on electricity produced by hydro. With 20 GW of installed capacity (16.9 GW hydro and 3.1 GW PHS) is an important hub for technology development. The country's rich potential also encourages further capacity additions and upgrades of existing stations.

In 2017, Switzerland completed the second stage of the Hogrin-Lema PHS station with capacity addition of 240 MW (IHA, 2017). The project has, thus, reached a total power capacity of 480 MW.

Norway

Norway's hydropower fleet includes 1660 plants with a total capacity of 33.75 GW. This is the highest capacity in Europe and 7^{th} highest globally (Figure 2). Norwegian hydro stations produce more than 140 TWh annually covering 95% of the electricity demand (two-thirds of final energy consumption). They also provide electricity and balancing services to neighbouring EU countries through the integrated Nord Pool electricity market. The extensive interconnectors' network allows exports that account at $\simeq$10% of the country's annual production.

The large and ageing hydropower fleet of Norway provide opportunities for upgrades and refurbishments, also taking advantage of the leading R&D activities of Norwegian industrial and research organisations (Kougias et al., 2019). Lysebotn II, a 370 MW project replaced the 210 MW station that was commissioned in 1953 (IHA, 2019). In total, Norway commissioned 419 MW of new hydropower during 2018. In early 2019, the Nordic Investment Bank (NIB) and Norwegian energy group E-CO Energi Holding AS decided to provide a EUR 181 million loan for the construction of three new medium-sized hydropower stations (Rosten, Nedre Otta and Tolga) and the expansion of an existing RoR project (Vamma) through the installation of a new, 128 MW Kaplan turbine (Water Power, 2019).

Norway hosts significant untapped potential for small-scale hydropower and an active market as shown by the more than 350 SHPs commissioned over the last 15 years. There is interest to further expand the SHP fleet in the following years, since the potential plant that have received concessions could produce 3.3 TWh on an annual basis (Røneid, 2018).

Iceland

Iceland has more than 2 GW of hydropower that produced approximately 13.7 TWh of electricity in 2018. In that year, Iceland increased its installed hydropower capacity by 100 MW at the Búrfell II project, an expansion of the Búrfell I station that utilises water of the existing reservoir (IHA, 2019).

Turkey

Turkey is a leading global market, with almost 1.1 GW of capacity added in 2018, hosting a total of 28.36 GW. Turkey's total installed capacity has almost doubled since 2009, when it was 14.55 GW, clearly showing the high growth rate. The country's estimated economical potential is 166 TWh/year and significant additions are needed to cover the growing demand that has been increasing on average by 5.5% since 2002 (IHA, 2019). According to estimations provided by the IHA, roughly 50% of the economic potential has been already tapped and a further 15% is under construction/near completion. In 2018, Turkey commissioned the 140 MW Kiği project and the 625 MW Upper Kaleköy project in the east part of the country. The 500 MW Upper Kaleköy project is planned for completion in 2020.

In early 2012, Statkraft begun the construction of the 517 MW Çetin project that comprises from two stations: the 401 MW Main Çetin and the 116 MW Lower Çetin. Once completed, the project would be the company's largest asset outside Norway. However, in 2016, Statkraft halted construction works (Harris, 2016) due to security concerns forced by a conflict between the Turkish government and Kurdish PKK militants. Expecting a loss of EUR 218 million due to the suspension, in September 2017, Statkraft sold the partially (20-30%) completed project to the Turkish group Limak Holding (Karagiannopoulos and Erkoyun, 2017). Limak will invest EUR 350 million to complete and commission the project in 2021.

The European Bank for Reconstruction and Development (EBRD) has provided loans to Turkish companies to support the energy generating sector and the increase of private participation in the energy sector. Latest example is the late 2018 EUR 50 million loan by the EBRD towards the Entek Elektrik Uretimi A.S for the privatisation of the 54 MW Kilavuzlu and 124 MW the Menzelet projects.

1.6 Hydropower development in the Western Balkans

EU strategies in the Western Balkans

Countries in the Western Balkans (Albania, Bosnia and Herzegovina, Serbia, Montenegro, North Macedonia, Kosovo[2]) host significant amounts of untapped hydropower sources. At the same time, they face increasing needs for electricity production due to their increased electricity consumption. Parallel to that is the need of countries like Serbia, Bosnia and Herzegovina and Albania to decarbonise their power sector, currently heavily dependent on coal- and lignite-fired stations.

An increasing interest is, thus, identified in the Western Balkans where only 1/3 of the hydropower potential has been developed so far ($\simeq$2.8 GW out of an estimated 8.4 GW). This activity is part of the reconstruction of the region's energy sector that was fragmented in the 1990s. This activity is of interest to EU due to the existing interconnections as well as the ongoing ones such as the Italy-Montenegro undersea cable that is expected to be operational in 2022, (eurelectric, 2017). Hydropower development in the Balkans is also important for the European industry. The Schall Group (Austria) has expressed its interest in building hydro and solar photovoltaic (PV) stations in Bosnia and Herzegovina worth EUR 6 million. Statkraft AS, a Norwegian hydropower company, organises its activities in Albania through the wholly owned subsidiary Devoll Hydropower Sh.A.

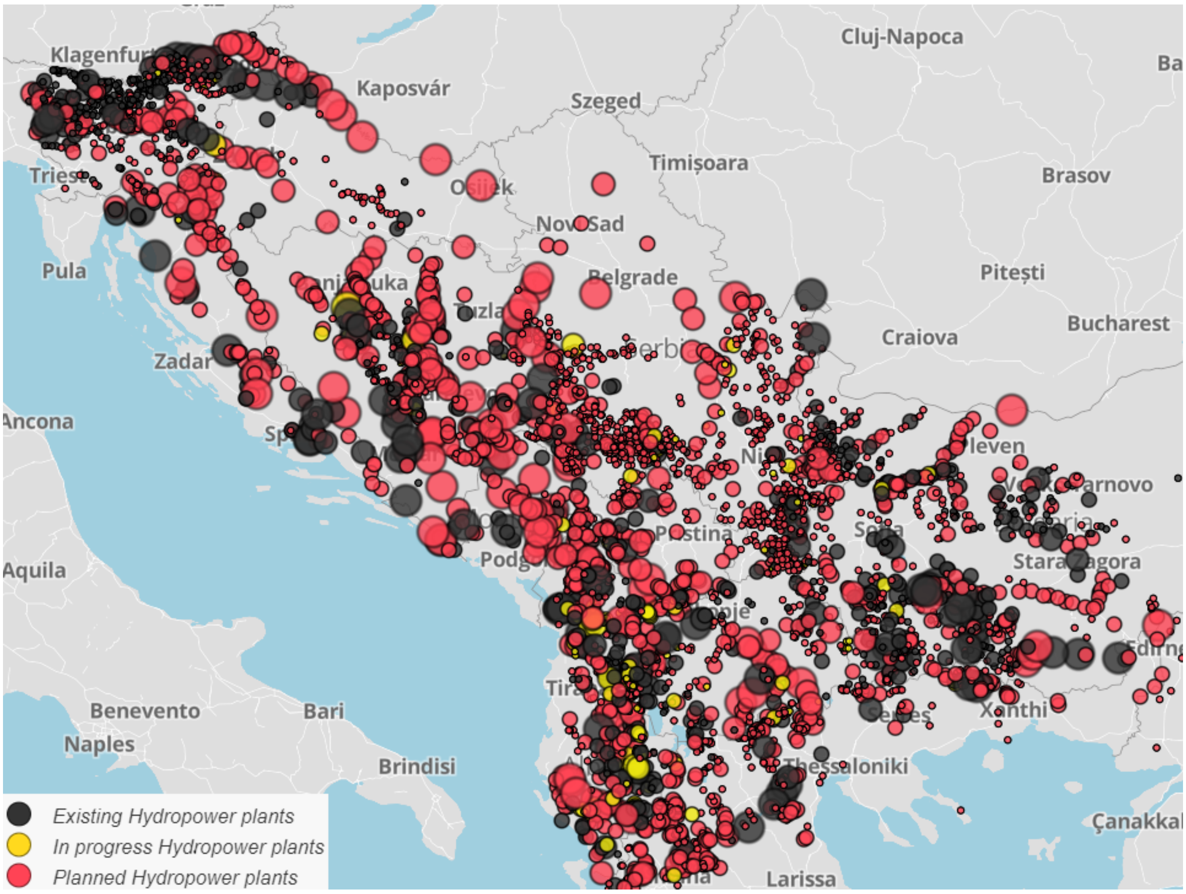

Figure 9: Existing, ongoing & planned hydro projects in W. Balkans. Source: (Balkan Rivers, 2019)

The currently operating hydropower fleet in the Western Balkans (Eurostat, 2018, eurelectric, 2017) includes more than 50 LHPs and approximately 250 SHPs in the six countries (Schwarz, Ulrich and Vienna, Fluvius, 2017, eurelectric, 2017). Figure 9 shows the location

[2]This designation is without prejudice to positions on status, and in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.

and size of hydropower plants that are either existing (in black), under development (in yellow) or in planning phase (in red) and covers the wider western part of the Balkan peninsula.

The European Union supports decarbonisation efforts also via the Western Balkans Investment Framework (WBIF). A dedicated website (https://www.wbif.eu) provides information on various projects covering the social, environmental, transport, energy sectors. Earlier, the EBRD had signed a Memorandum of Understanding to strengthen cooperation with the Western Balkan states with a focus on sustainable energy. With projects worth EUR 4.2 billion, energy is WBIF's second most active sector. To date, seven hydropower projects have been considered to receive EU support. The aim is to accelerate the implementation of projects considered advantageous. A short description of these projects and their status is provided in the following:

Skavica Hydro Power Plant, Albania

The Skavica LHP is a 132 MW hydro station ($\simeq$450 GWh/year) to-be-located upstream of an existing station. Construction activities are planned to start in 2020. The WBIF provided a EUR 1.5 million grant in 2017 to support the feasibility and environmental/social impact assessment studies. The project's total cost is estimated at EUR 247.5 million, EUR 206 million of which will be funded by loans.

Caplje Hydro Power Plant, Bosnia and Herzegovina

The Caplje LHP is a hydro station that would produce $\simeq$57 GWh/year. Its location was identified very near a town (5.3 km), making licensing and construction a challenge. In December 2011, the WBIF provided EUR €800,000 EU grant for the preparation of the feasibility study and the associated environmental impact assessment. The study was initiated in 2013 but was subsequently cancelled as the local authorities did not agree on the issue of the urban construction permit. Accordingly, the project was cancelled.

Krusevo and Zeleni Vir Hydro Power Plants, Bosnia and Herzegovina

The preparation studies for these projects started in 2010 revealing a potential of 24 MW. The WBIF provided a EUR 1.0 million grant to support the feasibility and environmental/social impact assessment studies. However, the EUR 41 million project was cancelled in mid-2014 due to mine clearance issues. Similar is also the situation for the Vinac LHP in Bosnia and Herzegovina (EUR 750,000 grant) and the Ozalj II hydro in Croatia (EUR 500,000 grant).

Babino selo Hydro Power Plant, Bosnia and Herzegovina

The Babino selo LHP is a hydro station that can produce $\simeq$59 GWh/year. The WBIF provided a EUR 750,000 grant to support the feasibility and environmental/social impact assessment studies, completed in mid-2016. The project's total cost is estimated at EUR 35.75 million, EUR 20 million of which will be funded by loans.

Cebren Hydro Power Plant, North Macedonia

The stalled Cebren LHP is planned to be revived with support provided by the WBIF. It is expected to have a power capacity of 333–347 MW and cost approximately EUR 553 million. The project financial split foresees loans of EUR 358.6 million as well as grants worth EUR 111.6 million.

Future projects in the Western Balkans states

The Western Balkans countries have revealed their future plans for hydropower development. The current limitations of high-voltage interconnections do not favour LHP projects that will provide electricity and storage services to the whole region. Accordingly, interconnection projects could trigger hydropower development especially as far as financing is concerned. Political disputes also challenge trans-boundary projects of large scale.

Montenegro

To date, Montenegro has only utilised 18% of its hydropower potential (eurelectric, 2017) with a total 658 MW of hydro that produced 1.03 TWh in 2017. Accordingly, the government has expressed its intention to significantly increase the hydropower fleet. Currently, 27 projects are in the development phase with the total investments worth EUR 740 million. In addition to that, Montenegro intends to install four new stations (238 MW – 694 GWh/annualy) on the Morača river at an estimated cost of EUR 540 million.

Serbia

The undeveloped potential of Serbia is estimated at 7000 GWh, located on the Drina and Danube rivers. The government of Serbia has announced plans to install two hydropower stations in existing dams as well as to upgrade 15 existing plants with the support of the European Bank for Reconstruction and Development (EBRD). The total additional power capacity is $\simeq$30 MW.

Serbia's plan to increase the share of modern RES has also prioritised the further expansion of PHS (currently 614 MW). Plans include the 680 MW Bistrica project with an estimated storage capacity of 60 GWh that will be located near the existing 104 MW Bistrica LHP. Djerdap 3 is a very large PHS (2400 MW) project that needs to be constructed in three phases. Currently, its its financing seems difficult as it will only be meaningful if the station sells services to the whole region.

Bosnia and Herzegovina

The untapped hydropower potential of Bosnia and Herzegovina is estimated at more than 6000 MW (IHA, 2018). So far, only about 40% of it has been exploited (2504 MW).

In 2015, the Republika Srpska signed a memorandum of understanding with the China International Water and Electric Corporation for the development of the 160 MW Dabar project ($\simeq$252 GWh/annually) (IHA, 2018). Eventually, in January 19, 2019 a Bosnian hydropower company, subsidiary of the Hidroelektrane na Trebisnjici (HET), invited bids for the construction and financing of the project (EUR 185 million). By then, several Chinese companies had expressed interest in taking part.

North Macedonia

The Government of North Macedonia plans s total 80 MW of SHP to be completed before 2020. The technical hydropower potential of the country is estimated at 5500 GWh, significantly higher than the 2017 output (1090 GWh) that were produced in the country's 674 MW hydro stations.

Albania

Albania produces almost all its electricity from its existing hydro stations. Being a net importer of electricity, the government supports additions of hydro capacity. In 2016, 38 SHP were launched in Albania (eurelectric, 2017).

The Devoll hydropower project started in 2014 and consists from two hydropower plants: Banje (73 MW, completed) and Moglicë (173 MW, to be completed in 2019) with a combined capacity of 256 MW and an expected annual production of 729 GWh. The Devoll river project is a EUR 535 million investment, developed by *Devoll Hydropower*, an Albanian registered company subsidiary of the Norwegian utility Statkraft AS.

In 2017, the 74.6 MW "Fangu" station was also completed. It is the first LHP in Albania that was constructed by a private company; Ayen Hydropower, a Turkish company that entered the Albanian energy market in 2012. Ayen is currently the larger private power producer in Albania with a portfolio that includes 102.5 MW of power capacity.

Future projects include the 108 MW Kalivac station on the Vjosa river. Initially, in 2012, Hydro S.R.L, a company based in Italy, signed contracts to construct the station. However, following a decision of the International Court of Arbitration that ruled in Albania's favour, the contract was dissolved. In early 2017, the Albanian Ministry of Energy and Industry announced a tender for the construction of the Kalivac LHP.

Between 2002 and 2017, the Albanian government has approved the construction of 338 hydropower plants with the total number of hydropower stations planned to be built by 2025 being 440 (eurelectric, 2017). However, in late January 2019, the energy and infrastructure minister announced a freezing of work on new hydro plants. The new minister, Belinda Balluku, took office in 17/1/2019 and intends to launch a review to balance economic development and the protection of the environment (Koleka, 2019). Accordingly, all non-operational contracts will be postponed until a detailed report will assess their status.

Kosovo[2]

Future plans of Albania also include a 200 MW station, jointly built with Kosovo[2] between Dragash and Prizren. As the Minister of Economic Development Valdrin Lluka revealed, the project will receive EUR 20 million support from the EU. As of late 2018, the joint project is very close to receiving final approval.

2 Hydropower market overview: industry, investments, R&D

2.1 Industry's market status and outlook

This section analyses the market position of the main global suppliers of hydropower equipment. It is the result of a thorough review of the annual financial reports of the main international companies. The selection of the companies to be analysed was based on their size and dominant role in the hydropower market. Accordingly, the leading global suppliers were analysed as they represent the majority of the installed hydropower capacity, worldwide.

ANDRITZ Hydro

According to the 2017 annual report, ANDRITZ hydro business fell short of its budget target (ANDRITZ Group, 2018a). The report highlights a very difficult environment in Europe mainly due to continuously low electricity prices. This is the reason utility companies have been hesitant to upgrade their existing hydro fleet. The order intake fell by 12% between 2016 and 2017, from EUR 1.500 billion to EUR 1.317 billion. Sales were respectively reduced by 10% from EUR 1.752 billion (2016) to EUR 1.583 billion (2017). Despite the decline in sales, the hydro business increased its profitability with the earnings before tax, depreciation, interest and amortisation expenses (EBITDA) margin increasing from 9.5% (2016) to 9.7% (2017). Actual EBITDA values decreased from EUR 167.2 million (2016) to EUR 154.1 million (2017).

However, these values are still lower than those reported in the years 2013–2015 where the annual order intake ranged between EUR 1.865 billion and EUR 1.719 billion and the sales ranged between EUR 1.805 billion and EUR 1.835 billion. In the 2013–2015 period the EBITDA margin of the hydro business was also higher, 9.8–10.1%. The slowdown in the hydropower business is also illustrated in the number of employees; more than 1000 positions were lost in three years. ANDRITZ hydro was employing 8339 workers in 2014, but this number was reduced at 7237 employees in 2017.

Following the results of 2017, Andritz stated that it was facing an "unchanged, challenging market environment, with only a few medium-sized projects awarded" (Bloomberg New Energy Finance, 2018a). The 2018 report (ANDRITZ Group, 2018b) shows an increase in the order intake (+9.8%), but the sales fell short by (-4.1%) in 2017. The increase in order intake is not illustrated in the EBITDA value that is 7.6% lower compared to 2017 and the $\simeq$3% reduction in the number of employees (see Table 3). Most of the individual projects awarded are in Asia since the global investment and project activity for electro-mechanical equipment for hydropower plants has remained at a moderate level during 2018.

The company's outlook for the future remains largely unchanged in the hydro business area, expecting an only moderate market development for electro-mechanical equipment. Again, the low wholesale electricity prices are identified as the main reason for postponing the upgrade-renovation of the European hydro fleet. New hydropower project development is expected in Southeast Asia and Africa because of the several LHP projects being in the planning phase. Overall, in the medium- to long-term the company only expect selective awards. A satisfactory project activity was noted in the pumps' sector.

Table 3: Key figures of the hydro business area of ANDRITZ in 2017 and 2018 (EUR million).

	2018	2017	+/-
Order intake	1,445.8	1,317.2	+9.8%
Sales	1,517.5	1,583.1	+1.3%
EBITDA	142.4	154.1	-7.6%
EBITDA margin	9.4%	9.7%	—

Source: ANDRITZ financial report (ANDRITZ Group, 2018a,ANDRITZ Group, 2018b)

GE Renewable Energy

GE Renewable Energy is a division of General Electric focusing on hydropower, onshore/offshore wind and solar power generation. It resulted from General Electric's acquisition of Alstom power and grid businesses in November 2015 for a purchase price of USD 10.1 billion. Accordingly, its headquarters are in Paris. Alstom was a leading manufacturer of hydropower equipment for more than 100 years.

In 2017, the Hydro segment of GE Renewable Energy accounted for 11%, fairly higher than the 2016 value of 8%. The core activities of GE Renewable Energy are, thus, the onshore wind that accounted for 86% in 2017. Revenues and profits were almost unchanged between 2017 and 2016. However, there was a significant increase compared to the 2015 values, mainly the result of the Alstom acquisition (GE Renewable Energy, 2018a).

Approximately 21000 employees work for GE Renewable Energy. According to GE Renewable Energy, two strategic projects were commissioned during 2018: the 600 MW Qiongzhong PHS station in China and the 360 MW Obervermuntwerk II PHS station in Austria. The 2018 report reports a modest increase of 3.3% in revenues, from USD 9.2 billion in 2017 to USD 9.5 billion in 2018 (GE Renewable Energy, 2018b). However, the segment profit has declined by 50% from USD 600 million to USD 300 million for the same period (see Table 4). Accordingly, the renewable energy technologies (RET) activities represented 1.5% of GE total profits, down from 6.8% for 2017. These values include both hydro, wind and solar technologies as GE did not report specific figures for hydro.

The hydro-related revenues in 2018 were equal to USD 800 million, slightly lower than the USD 900 million of 2017. The available information clarifies the share of hydro business segment in the total revenues (GE Renewable Energy, 2018a). In 2017 this was 11% while in 2016 it was 8% (USD 720 million).

Table 4: Key figures of GE Renewable Energy in 2016–2018 (USD million). The values refer to the renewables' sector as a whole.

	2018	2017	+/-	2016
Order intake	10,900	10,400	+4.8%	≃10,300
Revenues	9,500	9,200	+3.3%	≃9,000
Hydro revenues	800	900	-11%	720
Profit	300	600	-50%	≃600
Profit margin	3.0%	6.3%	—	6.5%

Source: General Electric financial report (GE Renewable Energy, 2018a,GE Renewable Energy, 2018b)

Voith Hydro

Voith Hydro is a leading system supplier for hydropower stations. It is a joint venture between Voith and Siemens, in which Voith holds a 65%. Voith Hydro, the hydropower division of the Voith Group, was formerly known as *Voith Siemens Hydro Power Generation*. In the past 140 years, Voith Hydro has supplied turbines and generators for almost one-third of the global hydropower capacity, including equipment for the largest hydro projects in the world i.e. the Three Gorges, the Itaipú and Belo Monte dams.

According to the 2018 annual report, hydro, a core activity for Voith, showed a much weaker performance on the account than expected (VOITH, 2018b). The challenging environment for hydropower development resulting in an *unexpected deterioration* and performed less well than planned by 20%. While in 2016/2017 the Group Division Hydro accounted for 33% of the Group's sales, in 2017/2018 this share fell to 26%. The orders received by

Voith Hydro was significantly below the previous year (-27% and accounted for EUR 0.857 billion (VOITH, 2018b). Voith highlights *a more intense competition* on the global hydropower market, as one important reason for the sales' reduction. An additional reason is that all key performance indicators were negatively impacted by currency effects. A delay in concluding the contract in a major project has also influenced the moderate annual performance of the hydro division.

The value of the orders received fell by 27.5% between 2016/17 and 2017/18, from EUR 1.180 billion to EUR 0.858 billion (see Table 5). This was contrary to the original plans that expected an appreciable increase or at least a stable performance for 2017/18. Sales were respectively reduced by 22% from EUR 1.381 billion (2016/17) to EUR 1.103 billion for the financial year 2017/18. Profitability has also decreased by 28%, from EUR 106 million (2016/17) to EUR 77 million (2017/18).

Table 5: Key figures of Voith Hydro in 2016 – 2018 (EUR million)

	2017/18	**2016/17**	**+/-**
Sales	1,103	1,381	-22%
Order received	858	1,175	-27%
Profit	77	106	-28%

Source: Voith Hydro financial report (VOITH, 2018b,VOITH, 2018a)

As far as SHP plants are concerned (Voith definition: $<$30 MW), the segment remained roughly at the level of the previous period. On the positive side, the company reports high demand for PHS mainly in China, where Voith was awarded a contract to equip the Tian Chi 1.2 GW station. The services business of Voith Hydro (HyDervice) received a number of orders, showing the rising demand for services.

Voith Hydro claims that the European hydropower level has remained at a low-level *due to the energy policy situation* (VOITH, 2018b). In 2017/18, Voith Hydro was awarded the modernisation of Vlanden PHS in Luxembourg as well as the construction of Alto Tamega LHP in Portugal.

It is worth mentioning that in mid-2018, Voith opened a subsidiary in Sydney, Australia and a new hydropower centre in Addis Ababa, Ethiopia. This activity shows the company's plan to increase its international activity, an aim of several Europe-based manufacturers of hydro equipment.

In 2017/18, Voith Hydro's investment in property, plant, equipment and intangible assets accounted for approximately EUR 13 million (2016/17: EUR 14 million), representing 14% of the group's total annual investments. Contrary to that, R&D spending for hydro was decreased. The decline in business activity resulted in a decrease of the number of employees working at Voith Hydro from 4507 in 2016/17 to 3927 in 2017/18. Voith Hydro, thus, fell by 580 and currently represents 20% of the total group's workforce. This is contrary to the Group's overall increased number of employees (VOITH, 2018b).

Voith Hydro's outlook foresees a dynamic policy environment, low energy prices and hydropower only partially benefiting from the EU need to decarbonise the energy sector. The great untapped potential in Africa is also highlighted. For the 2018/19 fiscal year, Voith Hydro anticipates positive conditions. However, the annual activity may fluctuate from year to year in a difficult to predict manner. Overall, slight growth is expected due to the need to modernise power plants in North America and Asia, where many hydro stations, after decades of operation, are reaching the end of their operating cycle.

2.2 Hydropower and job creation

In 2017, the hydropower industry accounted for 1.51 million jobs, worldwide (IRENA, 2018c). This figure refers to large-scale stations and does not include job created in small-scale projects that account for an additional 0.29 million jobs. Accordingly, hydro provided direct employment to ≃1.8 million people in 2017, representing 17.4% of the total employment in renewable energy. The US national hydropower association assumes higher values ranging between 2.5 and 3.5 million as it assumes an average 2–3 full-time equivalent per MW of power capacity (Navigant Consulting, 2009).

Employment in 2017 was 10% lower than that of 2016 and the lowest of the last five years. This drop was mainly due to the lower activity in China (-20%) and Brazil that together account 33% of the global employment (IRENA, 2018c).

Jobs in the industry span various value chain elements as project design, manufacturing, project construction and operation and maintenance (O&M). In general, hydropower sector hires engineers, technicians, and skilled workers. It also provides employment to an increasing number of scientists to study the environmental effects of hydro's operation. A wide range of scientists also participate in corporate or academic R&D activities. More than 60% of the global employment in LHP is found in O&M (0.93 million), while an additional 30% works on construction sites. The manufacturing segment, which is of high interest for the EU, creates 10% of the global employment as it is less labour-intensive (IRENA, 2018c).

In the EU, hydropower employed 75,900 direct employees in 2016 (EurObserv'ER consortium, 2017), experiencing a significant drop from the estimated 94,800 jobs in 2015. These figures are model estimations, the result of EurObserv'ER methodological approach that evaluates the economic activity of the sector and then expresses it into full-time equivalent employment. The methodology processes the money flows from investments in new installations, O&M activities for new and existing plants, as well as manufacturing and trading of hydropower equipment.

In the EU, hydropower jobs are concentrated in Italy (13,400 employees), Spain (10,900) and France (10,000), followed by Germany (5,200). Figure 10 shows the 2016 direct and indirect jobs of hydropower for each MS. It also shows the annual turnover for the same year (background column, right axis).

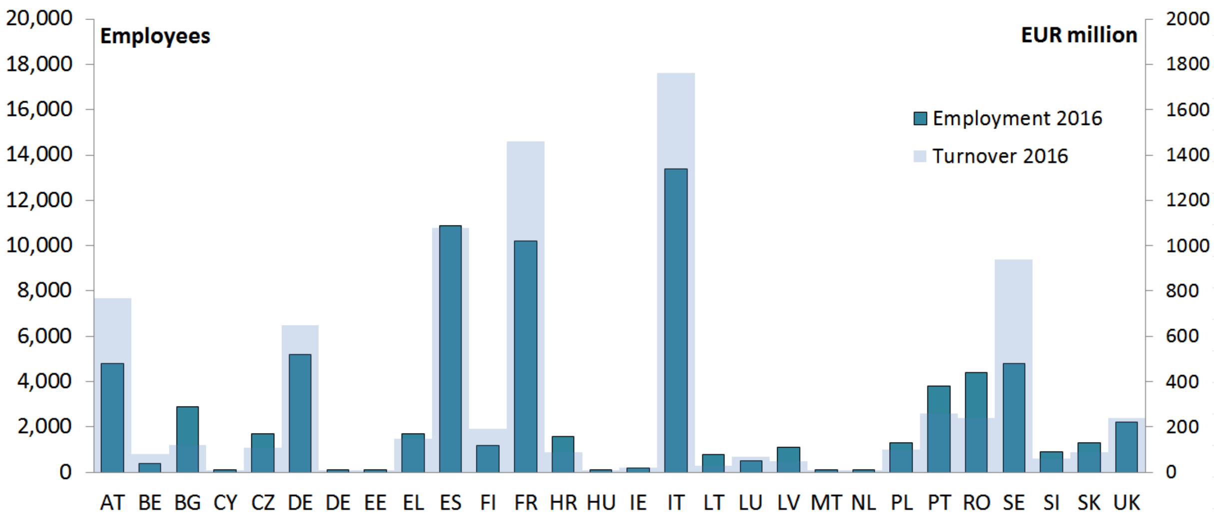

Figure 10: Employment and annual turnover of the EU hydropower sector in 2016. Source: (EurObserv'ER consortium, 2017)

2.3 Public and private research and development in EU

Public and private investment for hydropower technology R&D can play an important role, especially in sub-technologies and components that are at an early stage of development. Such initiatives allow technological concepts to be realised and steadily move towards experimental, pilot and full-scale applications. R&D activity can be measured directly through the capital invested in relevant actions. It can also be assessed indirectly by assessing the technological and safety output indicated by the patent activity and scientific publications. The present subsection builds on JRC's previous work on monitoring research innovation and competitiveness in the Energy Union priorities (Lepsa, 2015, Fiorini et al., 2017). In the following, public and private spending in hydropower R&D are presented. Moreover, the results of a patent analysis that covers different aspects of the technology are presented.

Public R&D investments

Figure 11 shows the annual public spending in hydropower R&D indicating a clear increase from 2009 and on. However, this increase is not consistent and appears to be driven by short-term national policies and specific programs. Indicatively, public spending in Ireland between 2009 and 2011 was high but it was not followed (or preceded) by proportionate investments.

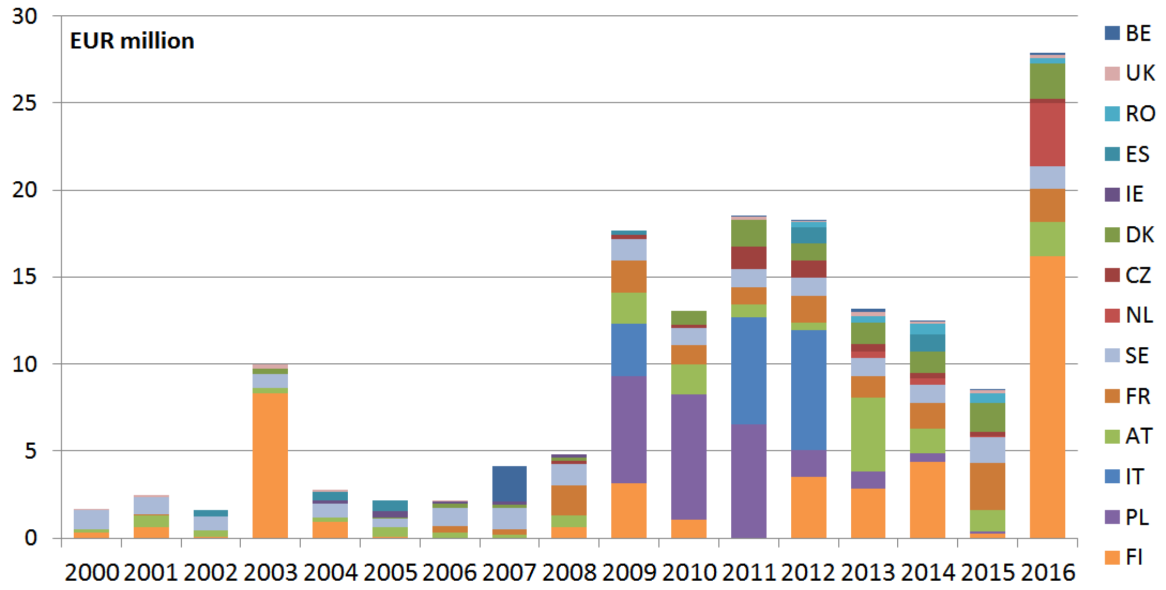

Figure 11: Public hydro R&D investments in EU (2000–2016). Source: (Pasimeni et al., 2018)

Figure 12 shows public spending in hydropower R&D per MS over the period 2000–2016. The graph focuses on MS that hosted significant R&D; investments were mostly leveraged in Finland, followed by Poland, Sweden, Austria, Italy, France and Germany. Public investment in Sweden is particularly consistent, with the annual spending being almost uniform over the analysed period. A similar consistency occurred also in France and Germany.

An interesting finding is the leading role of Finland and Poland. These MS host relatively small hydropower capacities 2.1% and 1.5% of the total installed hydro in EU. However, the government spending in hydro R&D appears to be significant. For Finland, hydro appears to be particularly important. On the one hand, Finland produces on average 19% of electricity at its hydro facilities. Moreover, Finland's large dependence on nuclear power requires the balancing role of hydropower. In the case of Poland, a likely explanation of the government's interest to promote hydropower is the untapped potential. According to estimations based on the European Hydropower database (HYDI) that was managed by the European Small Hydropower Association (ESHA), the utilisation of Poland's technical potential is the lowest in EU and equal to 17.2% (Steller, 2016). Poland being heavily dependent on coal electricity

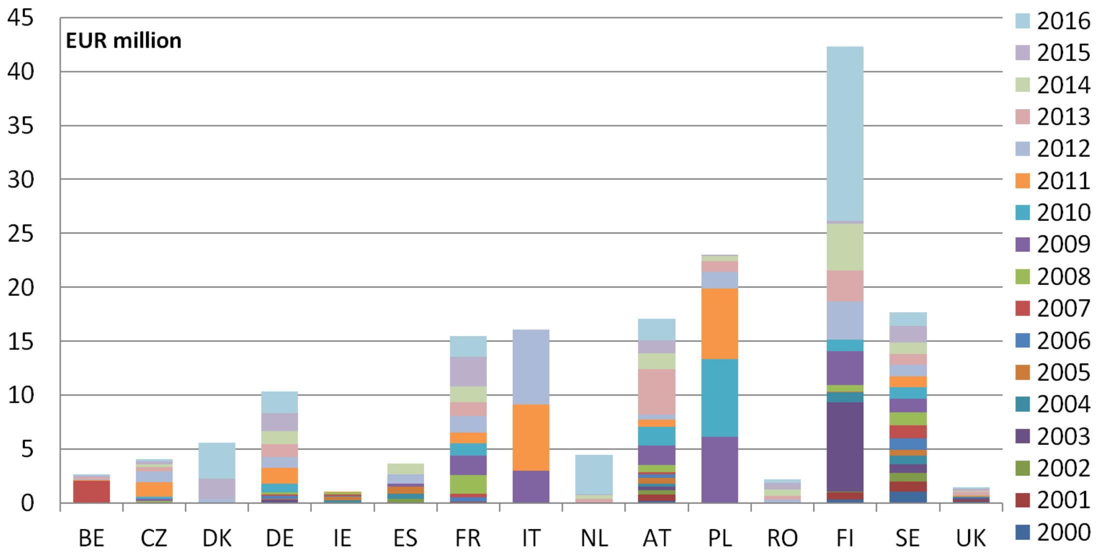

Figure 12: Public hydro R&D investments in EU (2000–2016). Source: (Pasimeni et al., 2018)

production, the decarbonisation of its power system will require significant capacity additions. Accordingly, it appears that the government intends to support locally-based technical knowledge and R&D in this technology.

Public investments in hydro R&D do not include EU funding provided in terms of the FP7 framework programme and Horizon 2020. Funding provided in terms of these research activities is presented in detail in the hydropower technology development reports of the Low Carbon Energy Observatory (LCEO) project (Kougias, 2016a, Kougias, 2018). Hydro-related projects of the framework programmes had a total budget of EUR 54.6 million, while H2020 projects (as of late 2018) additional EUR 41.4 million.

Figure 13 shows the global spending over 2000–2016. The analysis includes countries that have traditionally been important hubs for technological developments. The cumulative EU public spending was EUR 167 million ranked only after the United States (EUR 193 million). Canada's public investment has been similar to EU, EUR 174 million. It is important to highlight the public spending in Norway and Switzerland: EUR 86 and EUR 83 million, respectively. Public R&D in these neighbouring countries is often implemented in partnership with EU institutions.

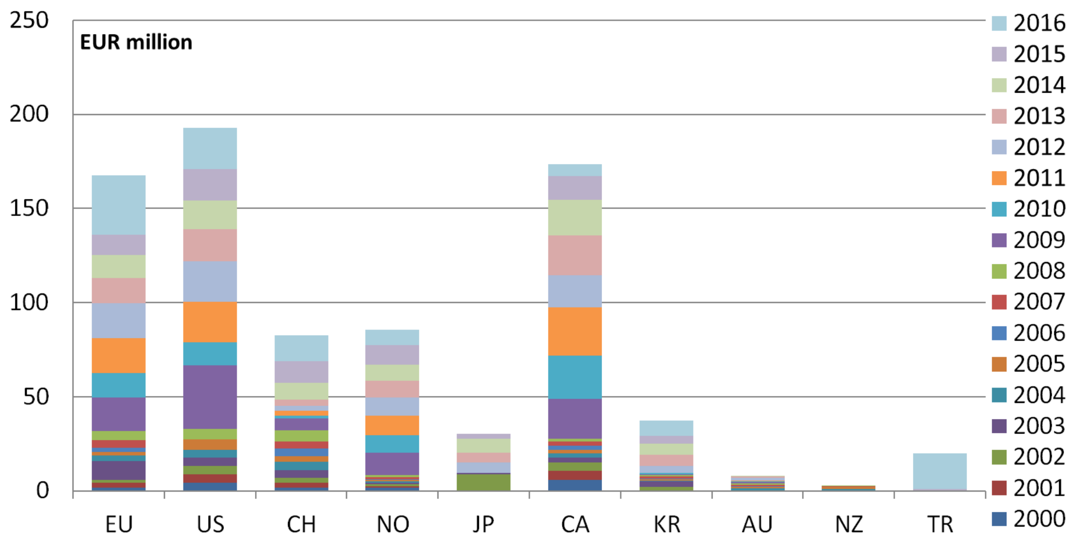

Figure 13: Public hydro R&D investments, globally (2000–2016). Source: (Pasimeni et al., 2018)

Private R&D investments

Figure 14 shows the private investment in hydropower R&D. The leading role of some MS was expected since they host the global leading companies in hydropower components manufacturing. This is the case of Germany (VOITH Hydro), France (GE Renewable Energy) and Austria (ANDRITZ Hydro). In the EU, R&D is mainly driven by private initiatives since corporate investments are more than 6 times higher than public ones, despite the shorter (−5 years) analysed time-frame of the analysis (Figure 12 vs. Figure 14).

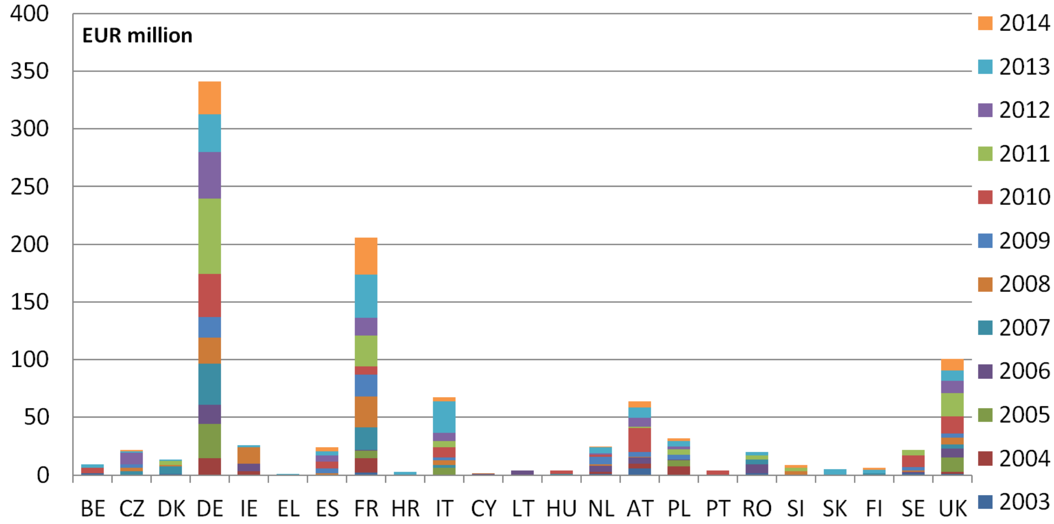

Figure 14: Private hydro R&D investments in EU (2003–2014). Source: (Pasimeni et al., 2018)

UK invested about EUR 100 million on hydropower R&D over the analysed period as it hosts a number of companies developing innovative (very) low-head, damless hydropower stations of the mini-scale, as well as different types of hydrokinetic systems. Poland's public and private spending are of similar scale EUR 23 million and EUR 32 million, respectively. As far as Finland is concerned, private investments were negligible, equal to EUR 6 million.

On a global scale, EU leads corporate R&D (see Figure 15) as the estimations show investments exceeding EUR 1.0 billion in the 2003–2014 period. This number is almost five times higher than that of US-based industry and shows the leading role of European industry. The provided investments are modelled estimations also based on patent activity. Given the very different procedure for patent granting in China, the country was excluded from the graph. Besides, during this time-frame China developed several GWs of LHP. The required tailor-made designs are expected to have favoured R&D investments.

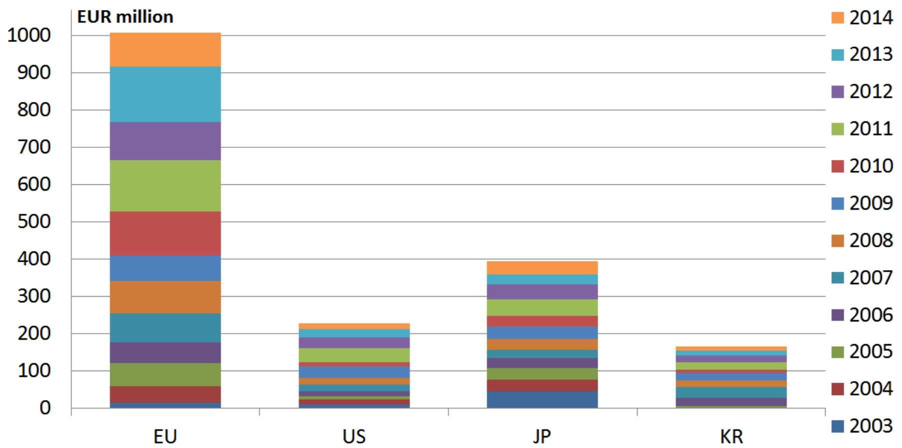

Figure 15: Private hydro R&D investments, globally (2003–2014). Source: (Pasimeni et al., 2018)

2.4 Patent analysis

Patents on hydropower are identified by using the relevant Y code families of the Coordinated Patent Classification (CPC) for climate change[3]. Relevant to hydropower are the following classes of patents:

Y02E Hydro energy: Energy generation through RES
- **10/20** Hydro energy
- **10/22** Conventional
  - **10/223** Turbines or waterwheels
  - **10/226** Other parts or details
- **10/28** Tidal stream or damless hydropower

Y02B Integration of RES in buildings
- **10/50** Hydropower

The present patent analysis was based on data available from the European Patent Office (EPO). The number of patents per MS are provided in Figure 16. The graph includes only countries with significant activity.

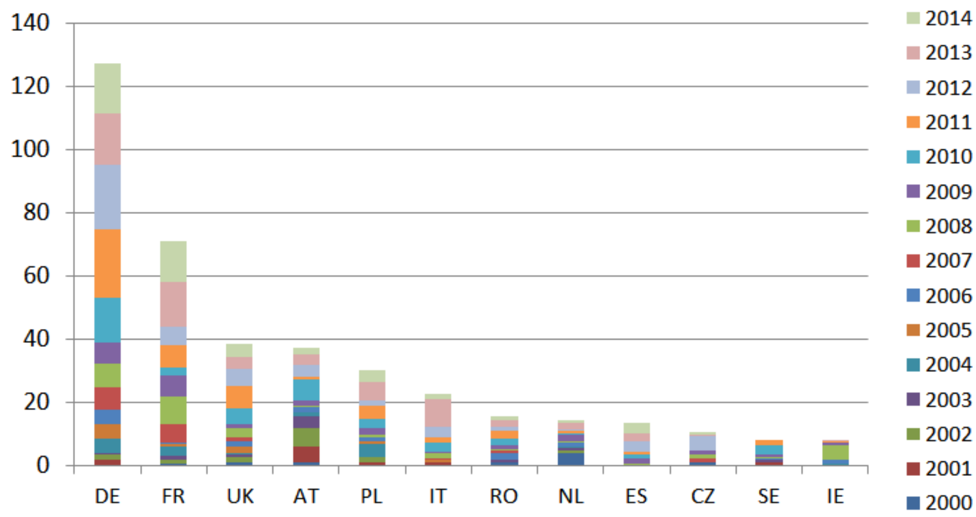

Figure 16: Patent activity in MS by number of inventions. Source: (Pasimeni et al., 2018)

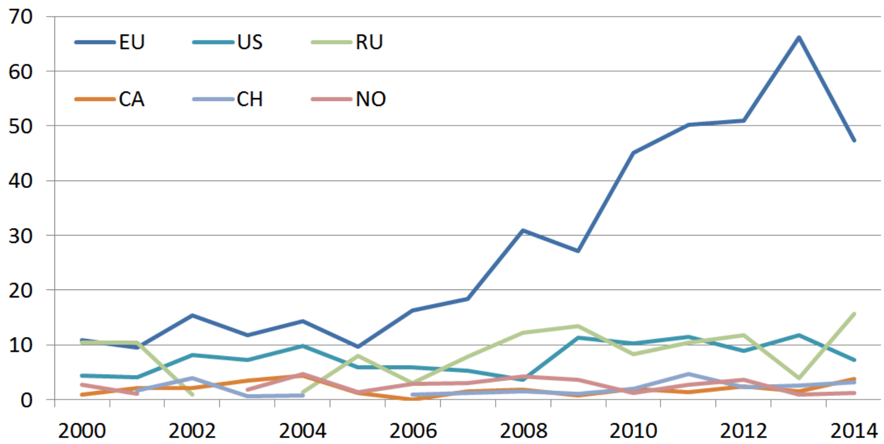

Figure 17: Patent activity in selected countries. Source: (Pasimeni et al., 2018)

[3]Information on the CPC codes is avaliable online at: http://www.cooperativepatentclassification.org

The patent activity in EU is higher than the US, Canada, Switzerland, Norway and Russia (Figure 17). Notable, of this group, it is the only area where the patent activity has an overall increasing tendency; it increased by a factor of six in less than a decade. However, when Japan, Korea and China are included, the picture changes. Patent activity in Japan has a long tradition with a slightly downward tendency (Figure 18). Patent activity in China has been increasing at impressive rates since 2010.

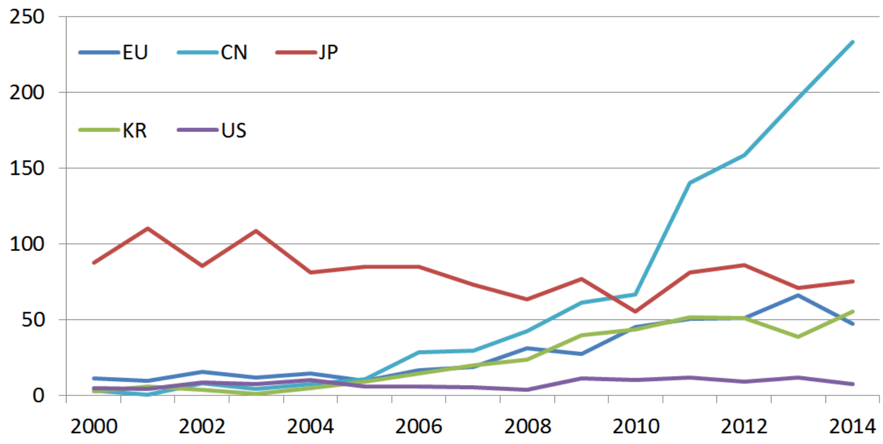

Figure 18: Patent activity in selected countries. Source: (Pasimeni et al., 2018)

Specialisation Index (SI)

The Specialisation Index (SI) represents the hydropower patenting intensity for a given country relative to the geographical area taken as reference. It is calculated using Equation 1:

$$SI = \left(\frac{\sum_i Patents}{\sum Patents}|_j\right) / \left(\frac{\sum_i Patents}{\sum Patents}|_{ref}\right) - 1 \quad (1)$$

i: technology; j: country considered; ref: reference geographical area, in our case the world.

According to the SI definition, if in a given country the $SI = 0$, the patenting intensity is equal to the global average. In case $SI < 0$, the country's intensity is lower than the world's average while if $SI > 0$ the intensity is higher (Fiorini et al., 2017). Figure 19 shows the SI for China, EU, Japan, Korea, and the US. EU's patent activity on hydro was below the global average until 2008. Since then, the SI has taken values near or higher than zero.

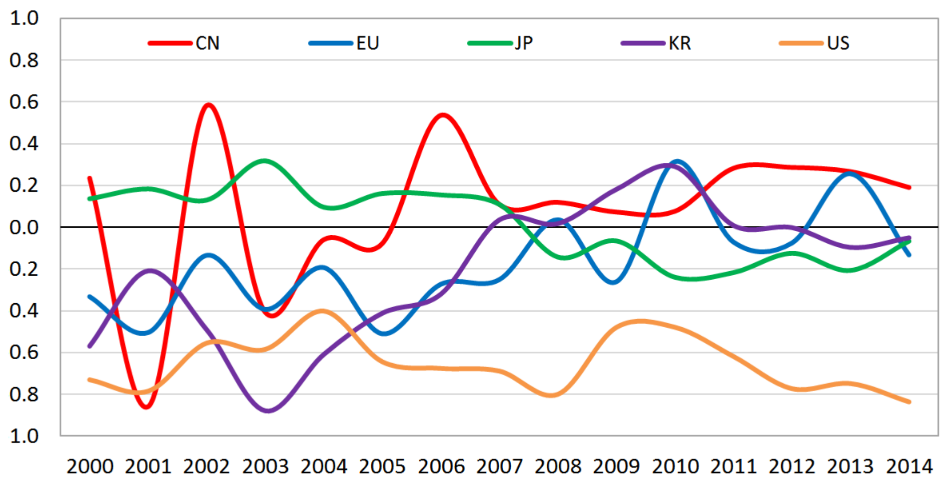

Figure 19: Values of SI for selected countries & EU (2000–2014). Source: (Pasimeni et al., 2018)

The SI analysis shows an upward trend for EU's patenting intensity during 2000–2014. Initially, EU reached the global average and, since 2010, showed a patenting activity generally above the global average. Similar to EU is the case of Korea. In Japan, however, patenting was well-above the global average until 2008 but decreased significantly since then. China's hydropower sector is the most active globally, while the US sector's activity is stable and constantly below average.

2.5 A global outlook of hydropower investments

It is generally difficult to track the trends in hydropower investments and particularly for large-scale projects because of the long licensing and construction periods. Moreover, it is challenging to define when such projects commence construction and when their operation starts. This is due to delays, disruptions or even stoppages of the construction of the dam and its filling. Moreover, in large-scale projects that host several units (hydraulic turbines), a partial operation of a hydropower project is a common strategy. Full power capacity is, thus, achieved gradually, as additional turbines are installed. For this reason, different sources may report different values of investments in the hydropower sector. The present report combined investment information from various sources in order to cross-check the available values.

In 2017, global investments in RES power accounted for $\simeq$EUR 260 billion and represented two-thirds of the total spending on power generation (IEA, 2018). As far as hydropower is concerned, investments were the lowest of the last decade, mainly due to a slowdown in the activities in China and Brazil. Investments in hydropower, thus, fell by $\simeq$30% from EUR 57 billion in 2016 (EUR 54 billion in 2015) to EUR 39 billion in 2017, the lowest value in ten years. The global overview presented in (Bloomberg New Energy Finance, 2018a), reports a similar value of EUR 39 billion for the 2017 global investments in large-scale hydropower. In the same year, global investments in wind power were almost twice as high, while the global investment in solar photovoltaic was three times higher than that on hydropower.

As far as the trends in future projects and investment decisions are concerned, 37 GW of hydropower was sanctioned in 2017 (IEA, 2018), significantly higher than that sanctioned in 2016 (12 GW), which was the lowest in more than a decade. However, this increasing trend in hydro projects' licensing and approval is mainly driven by new large-scale projects in China and does not reflect a resurgence in hydropower development in the EU.

The total power sector investments in Europe during 2017 was $\simeq$EUR 85 billion. A large part of this amount was directed toward development and upgrades of electricity networks (EUR 32 billion) and an additional EUR 5 billion for nuclear, coal and gas for power. Accordingly, the part related to power generation from RES was EUR 48 billion. Solar PV accounted for nearly EUR 8 billion, wind energy for the lion's share (EUR 30.5 billion) while EUR 6 billion was invested in other renewable energy technologies. Investments in hydro for the whole Europe accounted for EUR 3.5 billion, including PHS (IEA, 2018).

According to the latest BNEF reporting (Bloomberg New Energy Finance, 2018a), highlights of the year 2018 are four large-scale deals for hydropower stations, none of which in Europe. Asset finance deals include the Ituango 2.45 GW project in Colombia (total value USD 4.1 billion), the 420 MW Nachtigal project in Cameroon (value USD 1.4 billion), the Waneta dam in Canada (value USD 1.2 billion) and the Nam Theun project in Laos (USD 1 billion).

Investments in pumped hydropower storage

Narrowing down the analysis on PHS, it appears that investments decreased by $\simeq$60% in 2017, globally. Overall, $\simeq$3 GW of pumped storage was commissioned in 2017, a lower value than the previous year ($\simeq$5 GW) (IHA, 2018). This reduction was followed by a decrease in the share of PHS in the grid-scale electricity storage market. While PHS development accounted for at least 80% of the total storage market in the years 2013–2016, its share fell in 2017 at

≃70% (IEA, 2018). In 2017, China ordered the turbines of the 6 GW PHS project in Hebei.

Investments in small-scale hydropower

This section considers small-scale hydropower as hydroelectric facilities with a power capacity between 1 MW and 50 MW, a definition mainly adopted in Canada and China. This is not common in the EU context, where the term SHP generally describes hydroelectric stations with a power capacity that ranges between 1 and 10 MW, depending on the country definition. Since, however, the standard market analysis practice uses the 50 MW threshold, the present report also adapted the same definition for market assessment purposes.

In 2017, new investment in SHP (1–50 MW) was EUR 2.6 billion, 14% down from EUR 3.0 billion in 2016 (Bloomberg New Energy Finance, 2018a). This was a further continuing of a downward trend that started in 2014. The majority of the investments were made in developed countries with only the 6% being done in developing economies (Bloomberg New Energy Finance, 2018a). The main market is China that aims to bring the cumulative SHP capacity to 80 GW by 2020 according to its 5-year plan. Countries in South America and Russia have also financed hydro projects with a capacity below 50 MW. Overall, a total capacity of almost 3 GW of SHP was added globally in 2017.

In late 2016, the Asian Development Bank agreed to lend Pakistan EUR 287 million to install 1000 mini-scale hydropower systems and rooftop solar PV systems (Bloomberg New Energy Finance, 2018a). In 2017, Mozambique's Energy Fund launched a EUR 440 million rural electrification program to provide electricity to 332 villages with hydro projects of a total power capacity equal to 1 GW.

Future projections for investments

Apart from the corporate analyses and market analyses presented in §4.3, the present subsection provides the future projections provided by consulting entities. Analysts generally foresee a decrease in the future investments in hydropower. Accordingly, from the recent values of EUR 40–60 billion per year, estimations for the period 2021–2026 are expected to be lower and between EUR 30 and EUR 35 billion per year. Future projections for the period following 2026 and post-2030 foresee a further reduction in investments and a stabilisation at the EUR 15–20 billion per year levels (Bloomberg New Energy Finance, 2018b).

It is interesting to note that future investment projections expect a slow down of investment in China, the country that has led new project development in recent years. Analysts relate this slowdown to the opposition due to the environmental degradation caused by the mega-hydro projects. However, and despite environmental concerns, the Chinese government continues to support the announced target that hydropower capacity will almost double from 322.6 GW in 2015 and 600.5 GW by 2025 (GlobalData, 2018b). Projections for 2020 show an installed capacity of 442 GW (GlobalData, 2018c)

Projections anticipate a slight increase of the activity in India (between EUR 5 and EUR 7 billion/year) and a steady one in sub-Saharan Africa (SSA) (≃EUR 5 billion/year). Annual investments in the EU are expected to be only marginal. Overall, additional 300–320 GW of hydropower are estimated to be installed globally between 2018 and 2050 requiring investments of up to EUR 620 billion. The vast majority of these (three quarters) are expected to be installed in China, India, Turkey and Africa (Bloomberg New Energy Finance, 2018b).

GlobalData projections foresee a sustained interest and, contrary to the projections provided by Bloomberg, a growth in hydropower investments (GlobalData, 2018c). The analysis anticipates increase of annual investments at levels higher than EUR 70 billion per year by 2025, representing a CAGR of 2.5%. Country-wise, it is also anticipated that hydro will remain Canada's main source of power and forecasts an increase from the current ≃80 GW to 84.8 GW by 2025 (GlobalData, 2018a). This will be equal to a modest CAGR of 0.7%.

The REmap scenario for 2050 developed by IRENA anticipates a total 1828 GW of hydro by 2050, the equivalent of a CAGR of 1.07% (IRENA, 2018a). However, IRENA's projections for pumped hydropower storage are more ambitious and anticipate a total 325 GW of PHS in 2050, more than twice the currently installed capacity (CAGR equal to 2.08%).

Age of the EU hydropower fleet and refurbishment market

In terms of the present analysis datasets of hydropower stations in EU were further analysed (Hörsch et al., 2018). Information on the commission year and their retrofit year (if applicable) were not available for every station. However, it was available for the majority of them, representing almost 85% of EU's installed hydropower capacity ($\simeq$127.5GW). Figure 20 shows the results that corresponds to the stations for which information was available. It illustrates EU greenfield hydropower development over a 120-year period, at a 10-year time-step. It also shows the number of hydropower stations that were retrofitted during the same period.

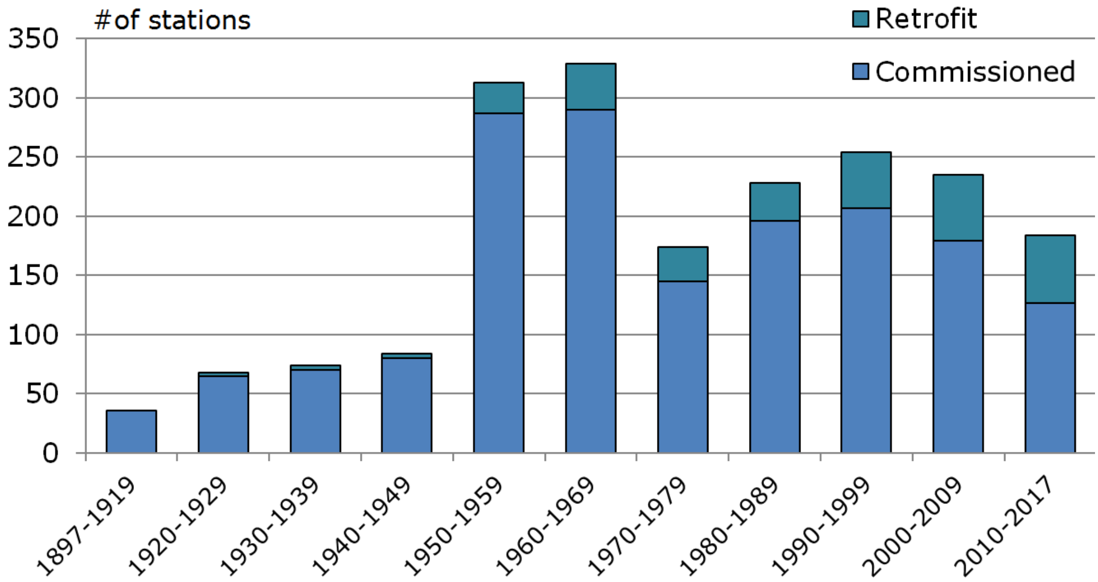

Figure 20: Hydropower greenfield development and retrofit in the EU (1897–2017).
Source: Author's compilation on PyPSA-Eur power plant data (Hörsch et al., 2018)

The analysis showed that the average commission year of EU's hydro fleet is the year 1973, with an average age of the stations being 46 years. This estimation does not take into consideration the 18% of the stations that have been retrofitted. Assuming that the retrofits performed a complete overhaul of the station, the average age of the fleet decreases by 4 years to 42 years. This only small reduction is due to the fact that approximately half of the refurbishments took place before 1990. Accordingly, it is reasonable to assume that the need for refurbishments and retrofits will continue to increase in the following years.

3 Outlook for the market using the JRC-EU-TIMES model

The JRC-EU-TIMES model (Simoes et al., 2013) offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050. The model provides projections on investments per power technology, capacity development, and the expected electricity production.

As far as hydropower is concerned, JRC-EU-TIMES model provides projections only for conventional hydropower installations. PHS stations, in certain cases a net consumer of electricity, are modelled separately, as storage capacities. Thus, JRC-EU-TIMES assesses PHS indirectly, by analysing the storage developments under different scenarios. The model was run with three basic scenarios:

Baseline: Continuation of current trends; it represents a “business as usual” world in which no additional efforts are taken on stabilising the atmospheric concentration of greenhouse gas (GHG) emissions; only 48% CO_2 reduction by 2050.

Diversified: Usage of all known supply, efficiency and mitigation options (including carbon capture and storage (CCS) and new nuclear plants); the target of 80% CO_2 reduction by 2050 is achieved.

ProRES: 80% CO_2 reduction by 2050; no new nuclear; no CCS.

Specific inputs include: a) capital expenditure (CAPEX) and fixed operation expenses (OPEX) cost trends, together with learning rate values for three hydropower deployment options: RoR, conventional reservoir LHP with advantageous characteristics (“LHP economical”) or located in less advantageous locations (“LHP expensive”); b) Load factor: country-specific values are included for the available resource in terms of full load hours per year, as well as an upper bound on installed capacity.

The CAPEX values used as an input for the LHP ranged between EUR 1090 and 3500 per kW of installed capacity. The model assumed higher values for small-scale stations (EUR 1410–4000 per kW) and mini-scale stations (EUR 1740–5000 per kW). RoR stations’ capital cost was estimated at the middle of this range at EUR 3000 per kW. The learning rates for the capital costs are expected to be very low, approximately 1–2% over the analysed period. Hydropower stations generally have low OPEX costs. Accordingly, OPEX was estimated at EUR 5–50/kW annually, with the highest values corresponding to mini-scale stations.

As far as the load factors are concerned, JRC-EU-TIMES model adopted the average values of hydropower productivity by using the capacity factor (CF) values recorded in the period 1990–2016 and provided by Eurostat. These values are presented in detail in §1.2. Accordingly, LHP stations were assigned relatively higher values (40%, on EU average) compared to SHP and mini-scale stations (37%, on EU average).

3.1 Outlook for the market

The model anticipates EUR 81–82 billion invested in hydro during the analysed period. This value is practically uniform in all scenarios, independently from the deployment of other renewable energy sources (RES). Indeed, under the ProRES scenario, that foresees large-scale installations of wind and solar, investments in hydro were only slightly reduced (EUR 81 instead of 82 billion). Figure 21 shows the cumulative EU investments for the analysed period projected by JRC-EU-TIMES. The almost uniform hydropower development (in light blue) is contrary to the very high variation shown in other RES such as wind and solar PV.

The total investments in EU plus Switzerland (CH), Iceland (IS) and Norway (NO) are expected to be ≃EUR 89 billion, over the same period. Breaking down the different periods

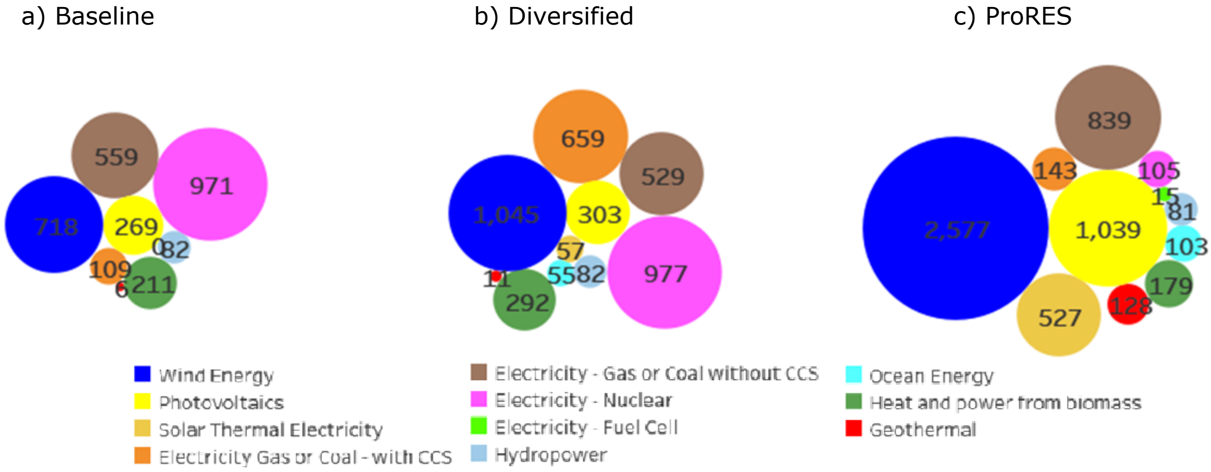

Figure 21: Modelled investment in power technologies 2020–2050 under the three basic scenarios. Source: JRC-EU-TIMES model

of the simulation for the Baseline scenario, a significantly increased activity is anticipated in the first period (–2020); on average, EUR 3.9 billion are invested in the analysed 31 countries on annual basis. Investments are expected to decrease to EUR 2.6 billion per year during the second decade of the analysis (2020–2030). In the last two decades of the simulation, investments shrink further and stabilise at EUR 1.2–1.3 billion annually.

According to the Diversified scenario, the total (EU plus CH, IS, NO) hydro investments slightly increase and are expected to reach EUR 92 billion by 2050. Similarly with the Baseline scenario, investments are concentrated until 2020 (≃EUR 4 billion/year), decrease at EUR 2.5 billion/year until 2030 and then converge to EUR 1.5 and 1.2 billion, respectively. The ProRES scenario anticipates EUR 90 billion invested in hydro in a similar pace (EUR 3.9 billion/year, EUR 2.4 billion/year, EUR 1.5 billion/year, EUR 1.1 billion/year). Hydropower investment projections for the three scenarios are provided in Figure 22.

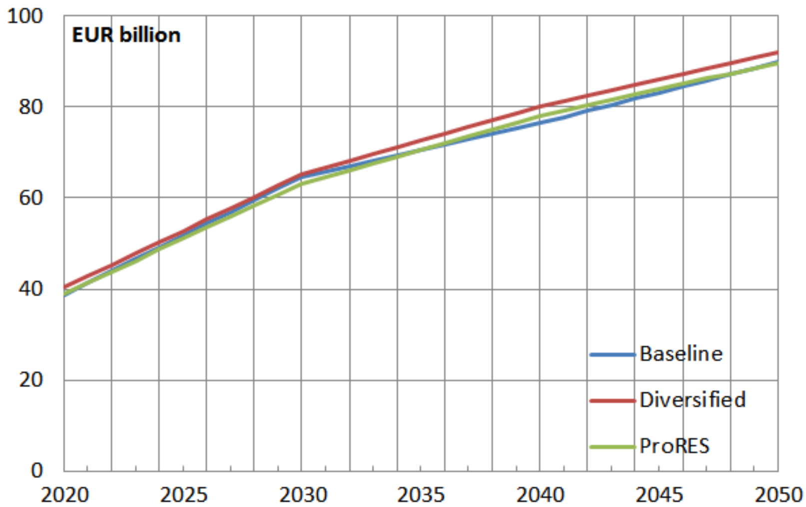

Figure 22: Cumulative investment projections 2020–2050 under the three basic scenarios. Source: JRC-EU-TIMES model

Country-wise, the largest investments are expected in France being EUR 21.7 billion over the analysed period and uniform among the three main scenarios. Investments in Italy are expected to worth EUR 11.1–13.6 billion, with the highest value corresponding to the Diversified scenario. Austria, Finland, Poland, Portugal, Sweden, Switzerland are expected to host investments ranging between EUR 3.7 billion and EUR 4.7 billion, in 2020-2050.

3.2 Deployment under different scenarios

Figure 23 shows an overview of the simulation results for the three main scenarios. Projected power capacities are provided for the years 2020, 2030, 2040, and 2050. Notably, all three scenarios anticipate similar results with very small deviations. Accordingly, the ProRES scenario, in spite of being favourable to RES deployment, does not foresee increased hydropower capacity additions.

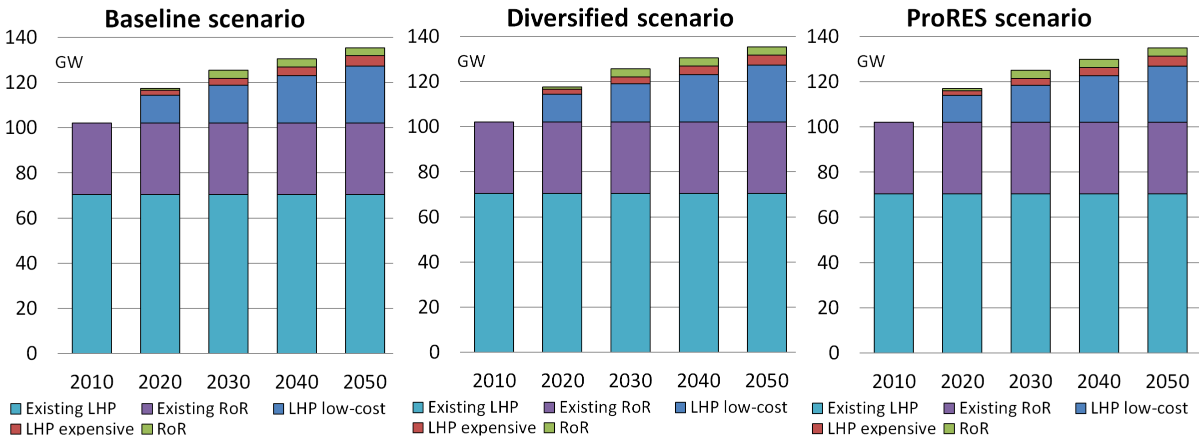

Figure 23: Distribution of the total installed power capacity (GW) of hydropower in EU for the baseline, diversified and proRES scenarios. Source: JRC-EU-TIMES model

The overall capacity additions for all the energy technologies are provided in Figure 24. In all scenarios, the role of hydropower in terms of power capacity remains unchanged.

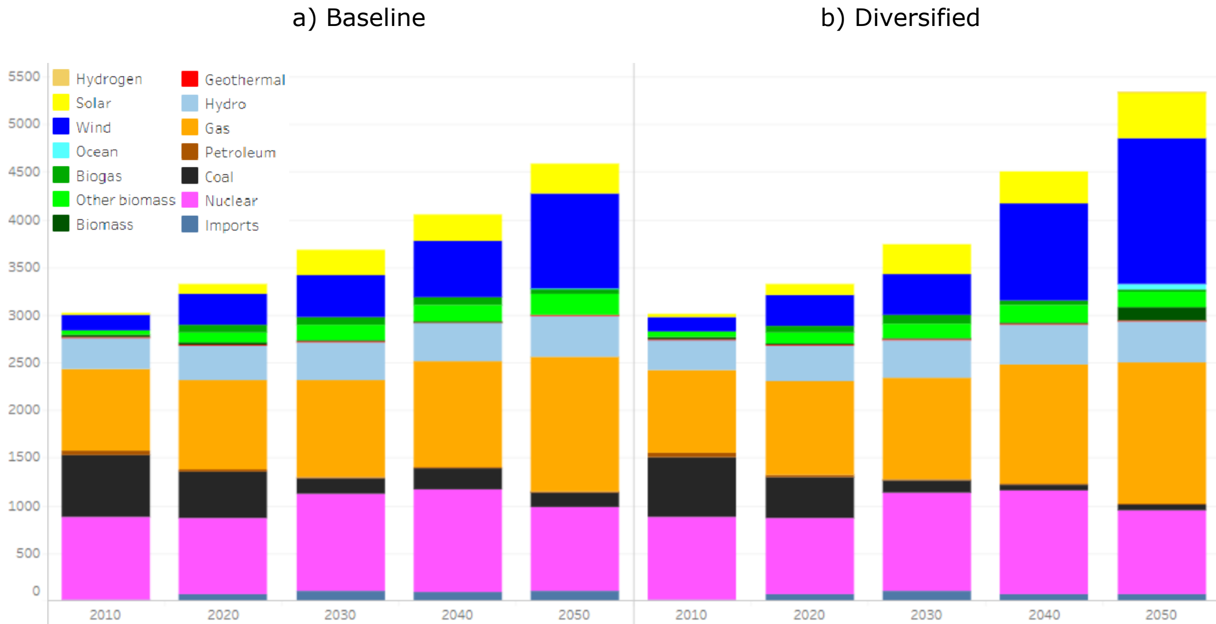

Figure 24: JRC-EU-TIMES model: distribution of power capacity (GW) by technology for the baseline and diversified scenarios. Hydropower is shown in light blue. Source: JRC-EU-TIMES model

The obtained results reflect the particularities of hydropower development. Hydropower is not modular like wind and solar PV power and can only be developed in specific locations where there exists hydro potential. Besides, in several EU member state large share of the untapped locations has already been utilised. Moreover, environmental and social opposition to large-scale projects hinders a higher growth rate such as the one of the period 1995–2002 (CAGR 9.8%, see Figure 3). Accordingly, new hydropower construction is the result of complex interactions rather than the selection of the technologically and/or economically advantageous option. For this reason, modelling future hydropower growth is more complex and uncertain compared to modern RES i.e. wind and solar.

Pumped hydropower storage

The results show that under the Baseline and Diversified scenarios, the need for additional PHS capacities is negligible (Figure 24). For the ProRES scenario storage requirements increase, due to the very high share of variable RES (solar PV, wind). However, this is not followed by proportional increases in PHS capacities. The ProRES scenario assumes that technological breakthroughs will render alternative storage technologies (batteries, hydrogen) cost-competitive in the mid-term. Accordingly, JRC-EU-TIMES anticipates negligible new PHS deployment under all scenarios.

3.3 Capacity additions per MS under different scenarios

It is generally not recommended to process results at country level when running energy modelling simulations at a continental scale. Such information may be misleading as the model is designed and fine-tuned in order to provide the projections at EU scale. Nevertheless, for information purposes, Figure 25 shows the conventional hydropower capacity additions in the EU member state as resulted from the baseline scenario of JRC-EU-TIMES. The contained information shows the distribution of the capacities added in every period to 2060, per country. According to the baseline scenario, 55% of the additions take place in France and Italy, the two leading countries in EU.

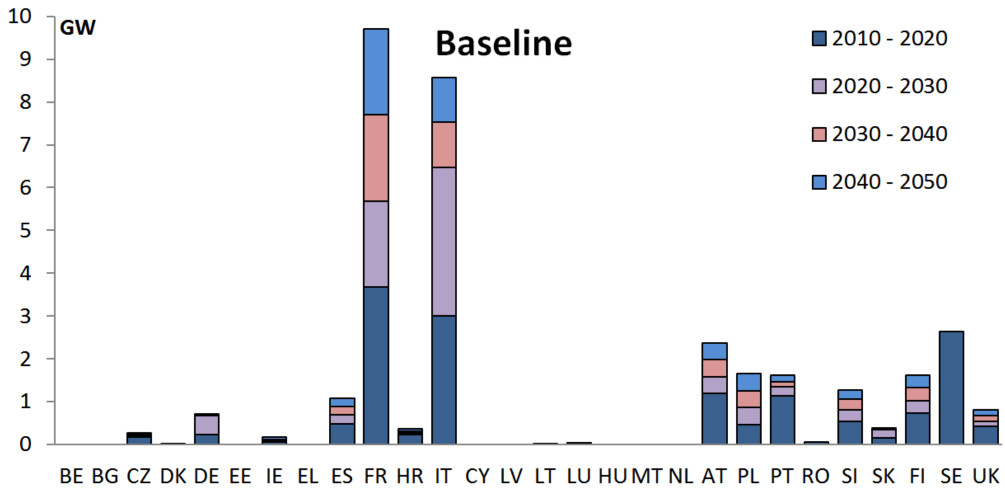

Figure 25: Modelled capacity additions for the Baseline scenario. Source: JRC-EU-TIMES model

Country-level projections for the two additional basic scenarios are provided in Figures 26 and 27. As mentioned, differences with the Baseline scenario are only minimal, if any. In total, a further 12 sensitivity cases were run with the results presented in detail in a dedicated LCEO deliverable (Nijs et al., 2018) that also explains the model's main features and presents all scenarios and results.

The practically uniform projections for hydropower growth are common in all 15 scenarios analysed by the JRC-EU-TIMES model. Even the ProRES scenario (Figure 27), with high technology learning rates, projects similar-low levels of deployment. This is due to the high technological maturity of hydropower that only allows minor improvements.

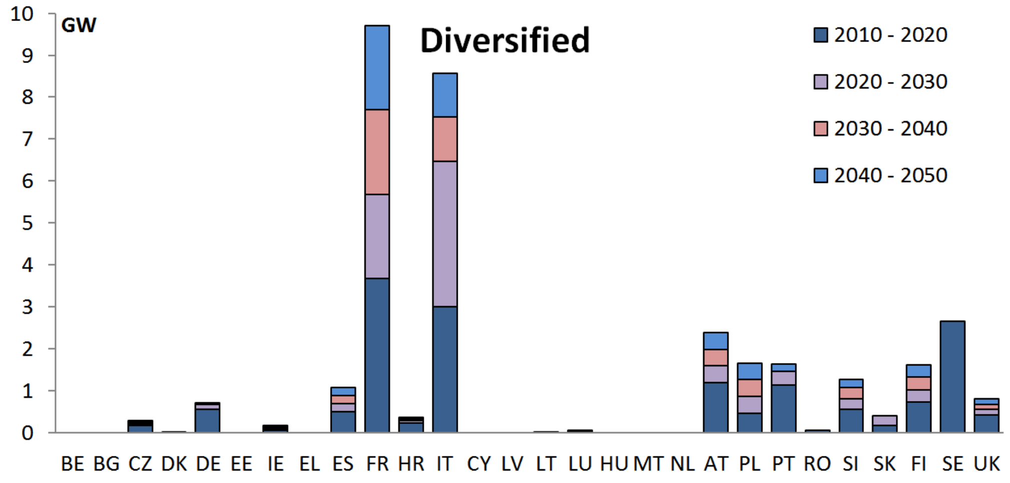

Figure 26: Modelled capacity additions for the Diversified scenario. Source: JRC-EU-TIMES model

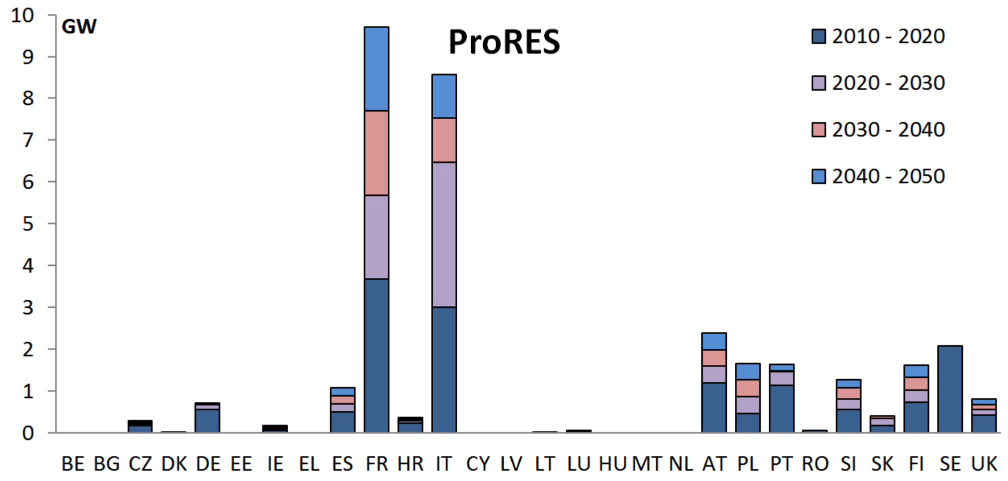

Figure 27: Modelled capacity additions for the ProRES scenario. Source: JRC-EU-TIMES model

3.4 Economics of hydropower

Hydropower is a capital-intensive technology with the major part of the investment being required at the early stages of development. This is the reason the cost of capital is very important for hydropower investments. Hydropower generally provides electricity at a very competitive cost. However, and due to its relevantly higher technological maturity compared to modern RES, further major cost reductions are not foreseen. This is also shown in the low learning rates of the technology that in the case of LHPs range between 1.4% and 2.63% (Rubin et al., 2015). Compared to modern RETs, these values are very low. According to the literature, onshore wind technology matured with a learning rate higher than >5%, while for solar PV the values generally exceeded 15%. There is evidence that the learning rates for SHPs and mini scale stations are significantly higher. This is particularly the case for designs supported by R&D activities. Learning by researching rates can reach values as high as 20.6% (Rubin et al., 2015).

3.5 Barriers to market expansion

According to the Intergovernmental Panel on Climate Change (IPCC), almost half of Europe's technical hydropower potential has already been developed (Kumar et al., 2011). Compared to North America's 40%, Latin America's ≃25%, Asia's 20% and Africa's <10%, it appears that most of the very advantageous locations in Europe have already been utilised. Europe's economic hydropower potential is even lower than that, as it excludes locations where investments cannot be profitable under the current technological and market conditions. Environmental constraints further reduce the available potential as permission for hydropower construction in protected areas is generally not granted. Thus, a specific barrier for Europe is the lack of a number of advantageous locations where new hydropower development would represent an attractive investment opportunity.

An important barrier to large-scale deployment may be the measures to protect the environment and river ecology that hamper new dam construction in EU rivers. This is due to the effort to simultaneously pursue RES and environmental goals, as described in the EU Renewable Energy Directive (RED)-II and the Water Framework Directive 2000/60/EC (WFD). Hydropower deployment is affected by the WFD, despite the fact that it is not directly covered by this legal framework. The WFD aims at securing a good ecological status of EU water bodies and the irreversible changes that a dam imposes to rivers creates a conflicting situation.

Moreover, hydropower needs to operate in accordance with EU's nature conservation policies and the requirements defined in the Habitats (92/43/EEC) and Birds (2009/147/EC) Directives. Such policies establish the EU-wide Natura 2000 ecological network that designates areas that need to be protected against potentially damaging developments (DG Environment, Management of Natura 2000 sites, 2018). In order to mitigate the effects of hydropower on freshwater ecosystems and habitats, licensing the construction of new greenfield projects in protected areas is challenging.

The impact of hydropower development on local ecosystems creates the necessity to involve the local authorities in decision making. Accordingly, local authorities are generally granted the responsibility to manage watercourse use rights for hydropower. European legislation on granting/renewing hydropower licensing is fragmented and varies among the various MS. The duration of such rights varies from few years (e.g. United Kingdom) to indefinite contracts (e.g. Sweden). The processes to provide and renew licenses also vary among the MS; in some countries, competitive tenders are organised, while in others such a process is not required (Glachant et al., 2015). The current status creates two main barriers to hydropower deployment: complexity and uncertainty. Both barriers are particularly important for hydropower business due to the high upfront investments that are required. Accordingly, long and complicated licensing processes significantly increase the investment risk of a hydropower project.

This is particularly important for the SHP that do not benefit from the economies of scale of conventional reservoir LHP. Installation cost of SHP is generally (proportionally) higher than that of LHP and delays in commissioning are a significant threat. Besides, the implementation of SHP projects is often managed by small companies that do not always have the means (resources, capital, manpower, expertise) to cope with long and complex procedures. Over the last years, the EU policy directions have focused on prioritising the deployment of SHP and run-of-the-river hydropower plants. This is due to their low environmental impact and the abundance of untapped locations. While certain MSs have fully utilised their SHP potential (e.g. Denmark, Sweden, Spain), others (e.g Italy, Greece, UK) have large capacities still untapped (International Center on Small Hydro Power, 2016).

4 Conclusions

Hydropower has provided clean energy for decades in the European Union. Installed power capacities significantly increased in the decade 1995–2005. Since then, and as a result of stricter environmental licensing requirements, hydro installations were only moderate. However, the role of hydro in power systems has remained very important. With a total annual generation of nearly 400 TWh of clean electricity, $\simeq$12% of the total net generation, hydropower's contribution is crucial for achieving the EU climate and energy targets. Reservoir hydropower is an important source of flexibility for the grid and PHS the dominant form of energy storage.

An important part of Europe's technical potential has already been utilised. This is estimated at more than 53% (Kumar et al., 2011) and includes the most favourable locations in terms of cost-benefit. Such a rate is high compared to e.g. Africa, where 92% of the technical potential remains untapped. A considerable potential, however, remains undeveloped in Europe and could contribute large quantities of clean electricity. According to the latest estimations, the technically feasible hydropower potential in EU is $\simeq$658 TWh/year (eurelectric, 2018), a 65% addition to the current values. A considerable and economically viable potential lies mainly in Sweden, France, Austria and Italy. Adding untapped locations in Norway, Switzerland and the Western Balkans, more than 1000 TWh of clean electricity (eurelectric, 2018) could be added to the annual clean electricity production in Europe.

A notable part of this additional production lies in existing stations and water infrastructure. Upgrading current stations can potentially increase their productivity and prolong their lifetime. Improvements include hydraulic machines and electric components that increase the power capacity, improve the efficiency and minimise losses. Moreover, they will also include state-of-the-art technology in monitoring, automation and control that will optimise the utilisation of the available water resources in relation both to energy production and the other services hydropower stations provide (e.g. irrigation, flood risk mitigation).

Apart from the technical and economic dimension, hydropower development needs to have positive social and environmental performance. Multi-purpose hydro projects are designed and operated to provide a wide range of important services such as water supply, irrigation, flood risk mitigation, and recreation. New dam construction may affect rivers' flow, obstruct sediment transport and affect the biodiversity and ecosystems including fish population. Good practices, especially for conventional large-scale hydropower projects, need to be identified and adopted in project design. Moreover, hydropower facilities with minimal environmental impacts need to be supported. This includes low-impact small-scale hydropower stations that, according to (Kougias, 2018), have not been utilised in several MSs.

In order to support the future role of hydropower in the EU further improvements in the regulation are required. A consistent and efficient licensing process is particularly important for hydro stations of the small- or mini-scale. Long and complex licensing procedures render such investments not feasible and of high risk. Incentives designed to support RES deployment should not exclude renewable hydropower and hydro-kinetic stations. It is a common case that auction schemes for RES do not foresee SHP capacities in several MSs. Support towards the hydropower industry and the outstanding knowledge maintained in numerous EU-based institutions could place EU in a leading position.

Investments in upgrading and retrofitting existing stations need also to be prioritised. The main driver for this is the high average age of EU's hydropower stations (>40 years) that need to maintain-improve their standards of safety, both physical and cyber. Retrofitting would also allow a prolonged operation of the existing stations at improved productivity and efficiency. It will also support the continuous and advanced provisions of hydropower's non-energy services. Pumped storage hydropower and flexibility facilities may become increasingly important as the share of variable renewable generation grows. Accordingly, policies should simplify new installations for storage and flexibility services, especially the closed-loop (also known as "pure") PHS stations that are not connected to the river network and do not involve negative impact on river ecosystems.

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List of Acronyms

CCS	carbon capture and storage
CAGR	compound annual growth rate
CAPEX	capital expenditure
CCGT	closed-cycle gas turbine
CF	capacity factor
CPC	Coordinated Patent Classification
EBRD	European Bank for Reconstruction and Development
EBITDA	earnings before tax, depreciation, interest and amortisation expenses
EIB	European Investment Bank
EPO	European Patent Office
ESHA	European Small Hydropower Association
EU	European Union
GHG	greenhouse gas
IHA	International Hydropower Association
IRENA	International Renewable Energy Agency
JRC	EC Joint Research Centre
LCEO	Low Carbon Energy Observatory
LHP	large-scale hydropower
MS	EU member state
NECP	National Energy and Climate Plan
NREAP	National Renewable Energy Action Plan
OCGT	open cycle gas turbine
O&M	operation and maintenance
OPEX	operation expenses
PHS	pumped hydropower storage
PV	photovoltaic
R&D	research and development
RED	Renewable Energy Directive
RES	renewable energy sources
RET	renewable energy technologies
RoR	run-of-the-river
SHP	small-scale hydropower
SI	Specialisation Index
SSA	sub-Saharan Africa
US	United States
WBIF	Western Balkans Investment Framework
WFD	Water Framework Directive 2000/60/EC

Table 6: Average capacity factor (CF) of the large-scale hydropower (LHP) fleet in each EU member state (MS) over the analysed period. Source: (Eurostat, 2016)

MS	Average (2010–2016)	Maximum (2010–2016)	Minimum (2010–2016)
BE	29.32%	38.64%	15.15%
BG	20.79%	29.58%	14.02%
CZ	17.53%	26.11%	10.02%
DK	0.00%	0.00%	0.00%
DE	55.26%	62.80%	47.77%
EE	0.00%	0.00%	0.00%
IE	36.02%	48.69%	28.43%
EL	21.13%	33.00%	11.31%
ES	24.60%	36.34%	14.77%
FR	37.28%	44.93%	28.37%
HR	41.71%	56.46%	29.82%
IT	33.81%	44.14%	26.27%
CY	0.00%	0.00%	0.00%
LV	20.72%	26.71%	13.07%
LT	44.44%	56.70%	35.51%
LU	0.00%	0.00%	0.00%
HU	47.56%	61.25%	35.42%
MT	0.00%	0.00%	0.00%
NL	30.09%	35.17%	17.59%
AT	55.29%	63.86%	48.72%
PL	50.13%	72.41%	37.35%
PT	29.68%	46.93%	13.38%
RO	30.34%	37.24%	21.81%
SI	46.48%	66.61%	37.31%
SK	30.92%	38.49%	23.68%
FI	47.35%	58.33%	35.50%
SE	46.29%	55.41%	38.17%
UK	29.29%	34.55%	19.33%
EU	37.12%	41.33%	33.90%

Table 7: Average capacity factor (CF) of the small-scale hydropower (SHP) fleet in each EU member state (MS) over the analysed period. Source: (Eurostat, 2016)

MS	Average (2010–2016)	Maximum (2010–2016)	Minimum (2010–2016)
BE	37.86%	47.26%	22.00%
BG	31.89%	47.65%	18.09%
CZ	26.80%	38.92%	17.72%
DK	0.00%	0.00%	0.00%
DE	56.66%	81.82%	36.54%
EE	0.00%	0.00%	0.00%
IE	35.83%	48.52%	28.27%
EL	33.95%	42.93%	20.73%
ES	27.89%	53.18%	8.69%
FR	32.61%	37.52%	24.87%
HR	34.08%	49.74%	20.76%
IT	37.91%	49.62%	29.49%
CY	0.00%	0.00%	0.00%
LV	0.00%	0.00%	0.00%
LT	31.61%	41.38%	21.40%
LU	0.00%	0.00%	0.00%
HU	40.49%	57.08%	25.94%
MT	0.00%	0.00%	0.00%
NL	0.00%	0.00%	0.00%
AT	44.35%	54.68%	28.41%
PL	37.51%	44.86%	30.00%
PT	30.99%	47.70%	18.07%
RO	18.63%	26.23%	10.18%
SI	37.35%	54.67%	27.27%
SK	18.89%	50.23%	4.25%
FI	36.96%	52.95%	24.95%
SE	43.25%	52.84%	31.53%
UK	24.43%	37.54%	0.00%
EU	35.48%	42.16%	30.52%

Table 8: Average capacity factor (CF) of the mini-scale hydro fleet in each EU member state (MS) over the analysed period. Source: (Eurostat, 2016)

MS	Average (2010–2016)	Maximum (2010–2016)	Minimum (2010–2016)
BE	28.81%	37.10%	21.56%
BG	31.97%	45.66%	16.44%
CZ	9.79%	13.82%	0.00%
DK	0.00%	0.00%	0.00%
DE	41.48%	52.96%	34.25%
EE	0.00%	0.00%	0.00%
IE	26.06%	43.59%	10.84%
EL	41.64%	48.38%	30.35%
ES	27.12%	61.69%	15.75%
FR	33.64%	42.29%	23.78%
HR	12.56%	28.54%	0.00%
IT	43.14%	53.71%	34.43%
CY	0.00%	0.00%	0.00%
LV	0.00%	0.00%	0.00%
LT	35.21%	44.99%	24.03%
LU	0.00%	0.00%	0.00%
HU	53.91%	68.49%	39.95%
MT	0.00%	0.00%	0.00%
NL	0.00%	0.00%	0.00%
AT	56.11%	99.49%	43.95%
PL	43.96%	56.44%	39.00%
PT	25.24%	31.75%	17.53%
RO	14.19%	23.48%	8.15%
SI	6.33%	8.15%	4.57%
SK	12.16%	21.95%	6.15%
FI	45.36%	108.45%	30.93%
SE	43.79%	67.59%	33.82%
UK	5.98%	18.65%	0.00%
EU	35.53%	38.83%	31.21%

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