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A COMPARISON ON DEVELOPMENT OF PUMPED STORAGE HYDROPOWER IN EUROPE AND ASIA-

An Analytical Case Study based on Pumped Storage Hydroelectric Projects developed in Europe and Asia in period 2010-2017

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Abstract

Energy consumption in European countries is increasing in significant amount each year. EU countries are becoming more concerned towards environmental safeguarding along with energy production. Wind and solar power have increased their market in many power systems in the recent decades and the main limitation is that they are greatly time dependent and are not available all the time to cope with variable energy demand. This limitation has led to the concept of a bulk energy storage system-Pumped Storage Hydropower.

Asia holds the largest share of global installed hydropower capacity of 611,063 MW and Europe has total installed hydropower capacity of 218,404 MW. Similarly, the PSH installed capacity of Asia is 67,850 MW and Europe is 50,949 MW. The characteristics of pumped storage hydropower commissioned in the present decade 2010-2017 in Europe and Asia have been compared based on annual addition of PSH capacity in grids, unit cost of construction, mode of use of PSH plants and ownership of PSHs,. Furthermore, the policies undertaken by countries in Europe and Asia are discussed and recommendations for PSH development are made. The results show that there are some measurable differences in development of PSH in Europe and Asia which includes differences in use cases, ownership and policies undertaken for PSH development.

Keywords: Renewable, Hydropower, Pumped Storage, Policy, Europe, Asia

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Abbreviations

EU	European Union
GW	Giga Watt
MW	Mega Watt
MWh	Mega Watt-hour
Mtoe	Million tons of Oil Equivalent
PSH	Pumped Storage Hydropower
TOS	Transmission Service Operator
TWh	Tera Watt-hour

1. Introduction

1.1 Background

The world has stepped ahead in search of clean reliable renewable sources of energy after realizing the severe impacts of global warming resulting from Carbon emission and radiation hazard due to malfunctioning of atomic energy plants. Different sources of renewable energy have been identified and most of them are greatly influenced by the seasonal changes on Earth. Some of the most harnessed sources of renewable energy are hydropower, wind energy, solar energy, biomass energy, tidal energy, etc. The major limitation of renewable sources is that they are greatly time dependent and are not available all the time to cope with variable energy demand. This limitation has led to the concept of storage type hydropower plants. As storage plants can address seasonal scarcity of water and can be operated corresponding to the variable demand, they have become very popular. The continuous increase in demand and substantial variation in demand with time has further stressed on optimization of available energy sources. A new type of hydropower plant was introduced to address this problem-pumped storage hydropower plant.

1.2 Definition

Pumped Storage Hydropower (PSH) is an innovative concept of hydroelectric energy storage used for load balancing. The energy stored in the form of gravitational potential energy of water is used repeatedly. The water is pumped into upper reservoir during the low demand of electricity using external energy, and during the periods of high demand the stored water is utilized through the turbines to produce electricity according to the required demand [1]. It differs from conventional hydropower plant in such a way that the water exiting from the turbine can be re-utilized the other way too, by consuming the energy which is in surplus in a distribution network and pumping it in the upper level reservoir. Schematic representation of a pumped storage hydropower is shown in Figure 1-1 [1].

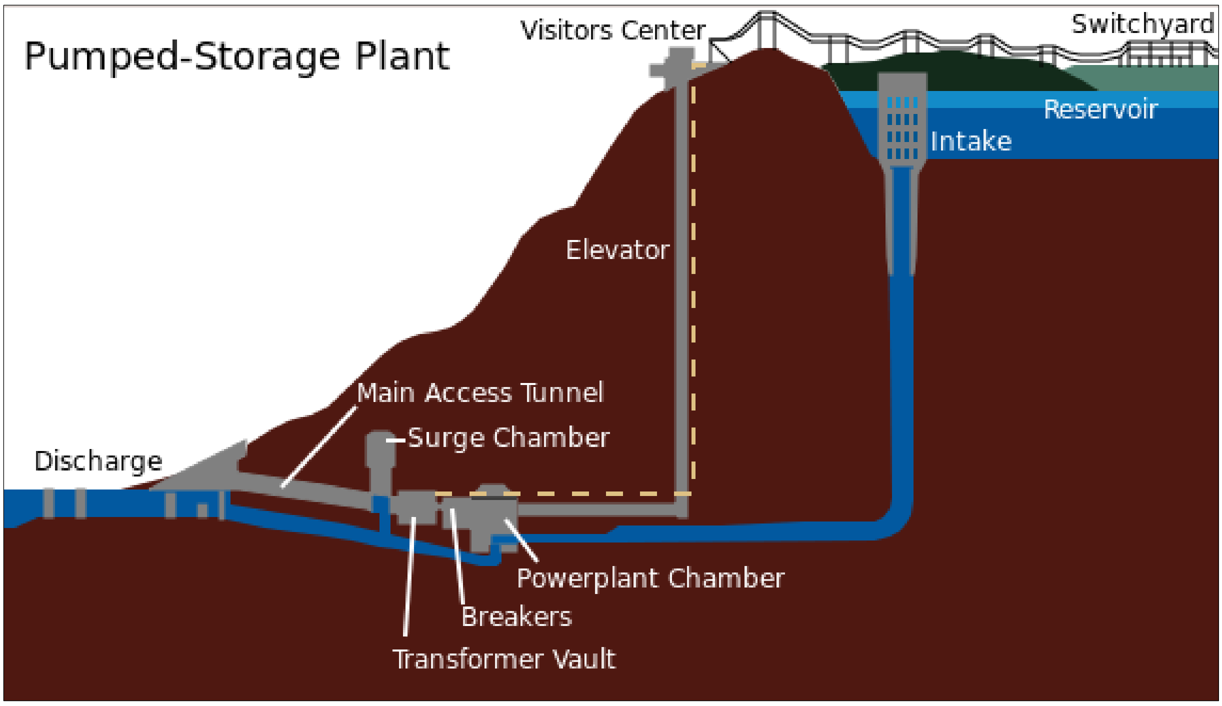

Figure 1-1 Typical diagram of Pump storage hydropower

Source: Retrieved from "https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity"

Since the countries are becoming more concerned towards environmental safeguarding along with energy production, Wind and solar power have increased their market in many power systems in the recent decades. Amongst all renewable energy sources, wind energy is the one with the largest economically feasible potential, but it is accompanied with the highest degree of variability, and unpredictability [2]. Hence, the high percentage of wind power plants in the generation mix is challenging the operation of power systems throughout the world. On the one hand, variability and uncertainty within wind power system require more advanced scheduling models, which have a direct impact on the amount and type of the required operation reserves. On the other hand, wind and solar power systems are much more influenced by instantaneous meteorological conditions which make them incapable of deciding their generation as per demand. Hence there may be excess energy during off-peak hours when conventional generators cannot reduce their output due to technical constraints. Thus, increasing the storage capability using technique like pumped storage plants, is a natural way to mitigate this problem [2]. The Figure 1-2 represents a typical example of power distribution of a pumped-storage hydroelectricity facility over a day.

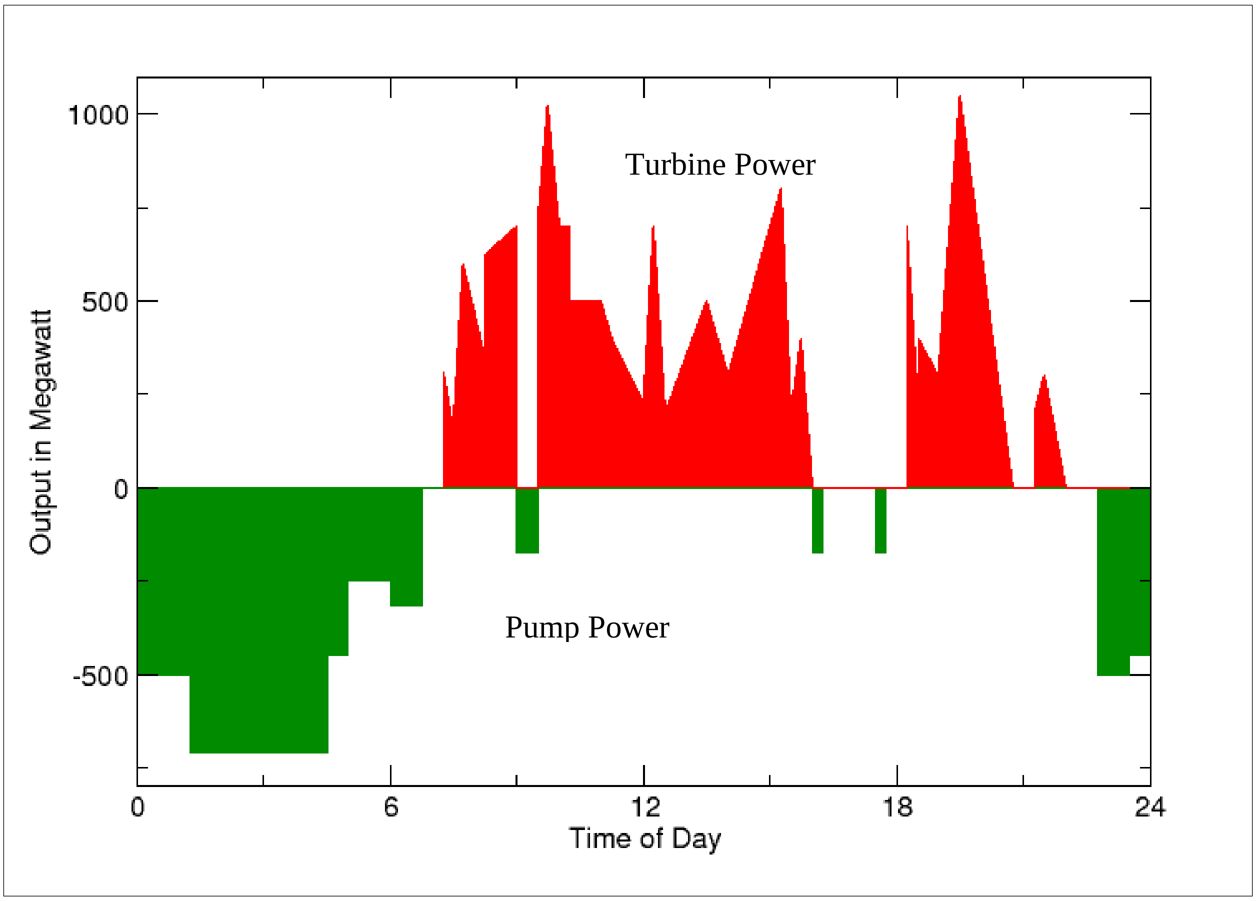

Figure 1-2 Typical example of Pumped storage hydropower operation

Source: Adapted from "https://commons.wikimedia.org/wiki/File:Pumpspeicherkraftwerk_engl.png"

As seen in figure 1-2, during off-peak hours (night time), the PSH plant is operated in pump mode thus pumping the water from lower reservoir to upper reservoir. Similarly, during peak hours (day time) the plant functions in generation mode using the gravity-flow of water from upper to lower reservoir.

1.3 Problem Statement

The EU countries are heading for replacement of the older sources of energy by renewable energy sources aiming to reduce carbon emission and environmental safeguard. Meanwhile, some of the shortcomings of major renewable sources like wind energy and solar energy such as intermittency in supply, no possibility of mass storage and less reliability led to the construction of bulk energy storage systems like storage hydropower and pumped storage hydropower. Similar is the case with countries in Asia. But since Asia consists of more developing countries experiencing acute shortage of energy, the scenario for consumption of energy and development of renewable energy are quite different. Same is the condition of hydropower development. With different scenario of demand and supply of electricity than Europe, developing Asian countries often face huge differences between demand and supply at both peak and off-peak hours.

Hence, this thesis research has attempted to draw out the general differences in consumption of energy, development of renewable energy including hydropower and use of pumped storage hydroelectric plants for power balancing in the grids.

1.4 Objective of Research

This thesis has attempted to give the overview of status of renewable energy, condition of hydropower development and compare the features of the pumped storage hydroelectric projects commenced in the period 2010-2017 and highlight development policies in development of pumped storage hydropower in Europe and Asia. The objectives of this research work are listed below:

a) General Objective
   - To know the status of energy consumption in EU-countries
   - To understand the development of Renewable energy in EU-countries.
   - To find out and compare the condition of hydropower development in Europe and Asia
   - To find out and compare the condition of pumped storage hydropower development in Europe and Asia

b) Specific Objective
   - To compare the characteristics of Pumped Storage Hydropower commissioned in the present decade 2010-2017 in Europe and Asia.
   - To understand the policies undertaken by countries in Europe and Asia for development of Pumped Storage Hydropower.

2. Literature Review

2.1 Status of renewable energy in Europe

The Renewable Energy Directive requires the European Union to fulfill at least 20% of its total energy need with renewable energy by 2020- which is to be achieved through the attainment of individual national targets. All EU countries must ensure that at least 10% of their transportation fuels come from renewable sources of energy [3].

A proposal published by the European Commission for revised Renewable energy Directive on 30 November 2016, requires to fulfill at least 27% of its total energy with renewable energy by 2030 [3]. The table 2.1 shows the gross consumption of energy in each of the European countries from 1990 to 2014.

Table 2.1 Gross inland consumption of energy, 1990-2014(million tons of oil equivalent)

	1990	1995	2000	2005	2010	2011	2012	2013	2014	Share in EU-28,2014 (%)
EU-28	1081.1	1082.7	1132.8	1191.3	1163.8	1105.5	1104.9	1106.6	1061.7	100
Belgium	31.5	34.4	37.6	36.6	38.6	35.2	35.0	36.2	34.0	3.2
Bulgaria	16.4	11.4	9.1	10.2	8.8	9.3	9.2	8.8	9.0	0.8
Czech Republic	32.5	26.1	24.8	26.0	24.9	24.1	23.7	23.9	23.0	2.2
Denmark	13.5	14.8	14.7	15.5	15.5	14.8	14.2	14.1	13.5	1.3
Germany	228.9	221.6	220.0	218.5	219.7	208.8	212.1	217.7	208.9	19.7
Estonia	5.7	2.6	2.4	2.9	2.9	2.8	2.9	2.9	2.8	0.3
Ireland	7.3	8.0	10.8	12.6	12	10.9	10.6	10.7	10.8	1.0
Greece	14.7	15.8	18.7	21.0	19.1	19.0	17.1	15.3	15.6	1.5

Spain	57.1	64.0	79.9	97.8	89.1	86.7	83.2	80.8	79.2	7.5
France	136.2	143.5	155.3	160.2	155.0	143.8	148.0	151.9	141.7	13.4
Croatia	6.5	5.3	6.0	7.2	7.2	7.0	6.7	6.6	6.2	0.6
Italy	107.7	114.6	124.7	137.2	128.5	123.1	121.8	118.5	113.4	10.7
Cyprus	1.1	1.4	1.6	1.8	1.9	1.9	1.8	1.6	1.6	0.2
Latvia	6.4	3.8	3.3	4.0	4.1	3.9	4.0	3.9	3.9	0.4
Lithuania	9.7	4.6	3.8	4.6	4.8	4.7	4.8	4.7	4.8	0.5
Luxembourg	3.3	3.1	3.5	4.5	4.3	4.3	4.2	4.1	4.0	0.4
Hungary	19.9	16.2	16.1	18.2	16.5	16.1	14.8	15.3	15.4	1.4
Malta	0.3	0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.1
Netherlands	41.8	51.0	52.3	54.2	55.1	51.6	51.5	51.6	47.3	4.5
Austria	19.3	21.4	23.7	27.8	28.0	27.1	27.0	27.9	26.8	2.5
Poland	59.9	62.9	55.3	58.5	66.4	64.8	64.4	63.3	61.6	5.8
Portugal	11.9	13.9	17.9	19.0	18.1	17.3	16.0	15.9	15.8	1.5
Romania	40.8	27.0	22.8	24.7	22.6	22.8	22.8	21.8	21.7	2.0
Slovenia	3.7	4.1	4.5	4.9	5.0	5.0	4.9	4.8	4.6	0.4
Slovakia	15.2	11.0	11.0	11.6	11.5	10.8	10.3	10.6	10.1	0.9
Finland	21.7	22.0	24.3	25.2	26.2	25.0	25.2	24.7	24.4	2.3
Sweden	31.2	35.1	35.0	33.7	34.1	32.4	32.4	31.6	31.2	2.9

United Kingdom	136.9	142.7	153.2	152.7	143.3	132.0	135.9	137.2	129.8	12.2
Iceland	1.4	1.5	1.9	2.0	2.5	2.7	2.7	2.9	2.9	-
Norway	16.1	16.9	18.1	18.6	19.6	18.7	18.8	19.0	18.4	-
Montenegro	-	-	-	0.8	0.8	0.7	0.7	0.7	0.6	-
FYR of Macedonia	1.4	1.5	1.6	1.7	1.8	1.9	1.8	1.8	1.7	-
Albania	1.9	0.9	1.5	1.9	1.9	2.0	1.9	2.0	2.1	-
Serbia	11.8	6.1	6.9	9.6	9.0	9.2	8.5	8.3	7.8	-
Turkey	38.6	45.1	56.2	63.4	74.0	78.7	84.2	82.9	85.9	-
Bosnia and Herzegovina	3.3	0.8	1.2	1.5	1.9	2.0	2.0	1.9	4.5	-
Kosovo	-	-	0.8	1.0	1.2	1.3	1.2	1.2	1.2	-

Source: Retrieved from “https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive”

From Table 2.1 it is clear that the general trend in consumption of energy is increasing since 1990. In case of some countries including Norway, the trend is somehow fluctuating from the year 1990 to 2014 [4]. This increase in demand of energy has further stressed on the available sources of energy.

The figure 2-1 gives the general overview of trend of primary production of energy from renewable energy sources in EU countries from 1990 to 2014. Out of the total of 1081.1 Mtoe of energy in 1990 almost 70 Mtoe that is 6.47% only was contributed by renewable energy while in 2014 out of 1061.7 Mtoe of total energy consumption in 2014, almost 190 Mtoe that is 17.9% was contributed by renewable energy. This shows the increased priority to renewable energy production by EU countries.

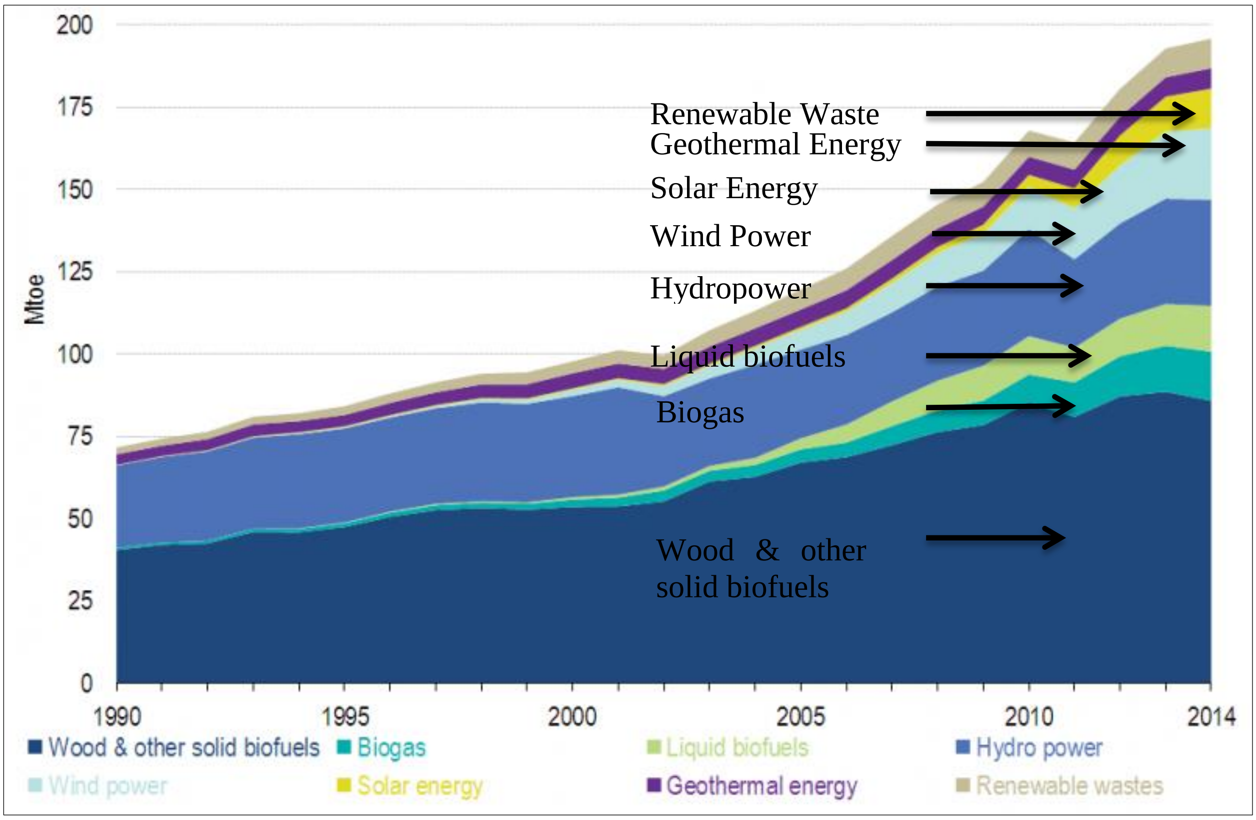

Figure 2-1 Primary production of energy from renewable source EU, 1990-2014

Source: Adapted from "http://ec.europa.eu/eurostat/statistics-explained/index.php/File:RENEWABLES-EU28-PRIMARY-PRODUCTION-2014.png"

From figure 2-1 it is observed that the production of renewable energy is increasing with a gentle slope from 1990 to 2005. After 2005, the rate of addition of renewable energy is increasing rapidly. This may be due to the policies undertaken by EU countries to emphasize production of renewable energy to replace energy consumption from non-renewable sources. It is observable from the figure that after wood and other solid biofuels, Hydropower is the major source of renewable energy as compared to the Biogas, Solar, Geothermal since 1990 to 2014. Almost 75 Mtoe of renewable energy is contributed by Hydropower alone among total 190 Mtoe in the year 2014, which is approximately 40% of the energy produced from renewable source [5].

2.2 Status of electricity from renewable energy sources in Europe

Different policies changes have been made and signed by the countries to emphasize the production of renewable energy which has led to significant increase in proportion of renewable energy. Figure 2-2 shows the further classification of renewable sources and their status from 2004 to 2014. It is observed that the Hydropower contributes the most in the production of electricity from renewable resources followed by wind turbines and Biomass & renewable waste in European Union [6] from the year 2004 to 2014.

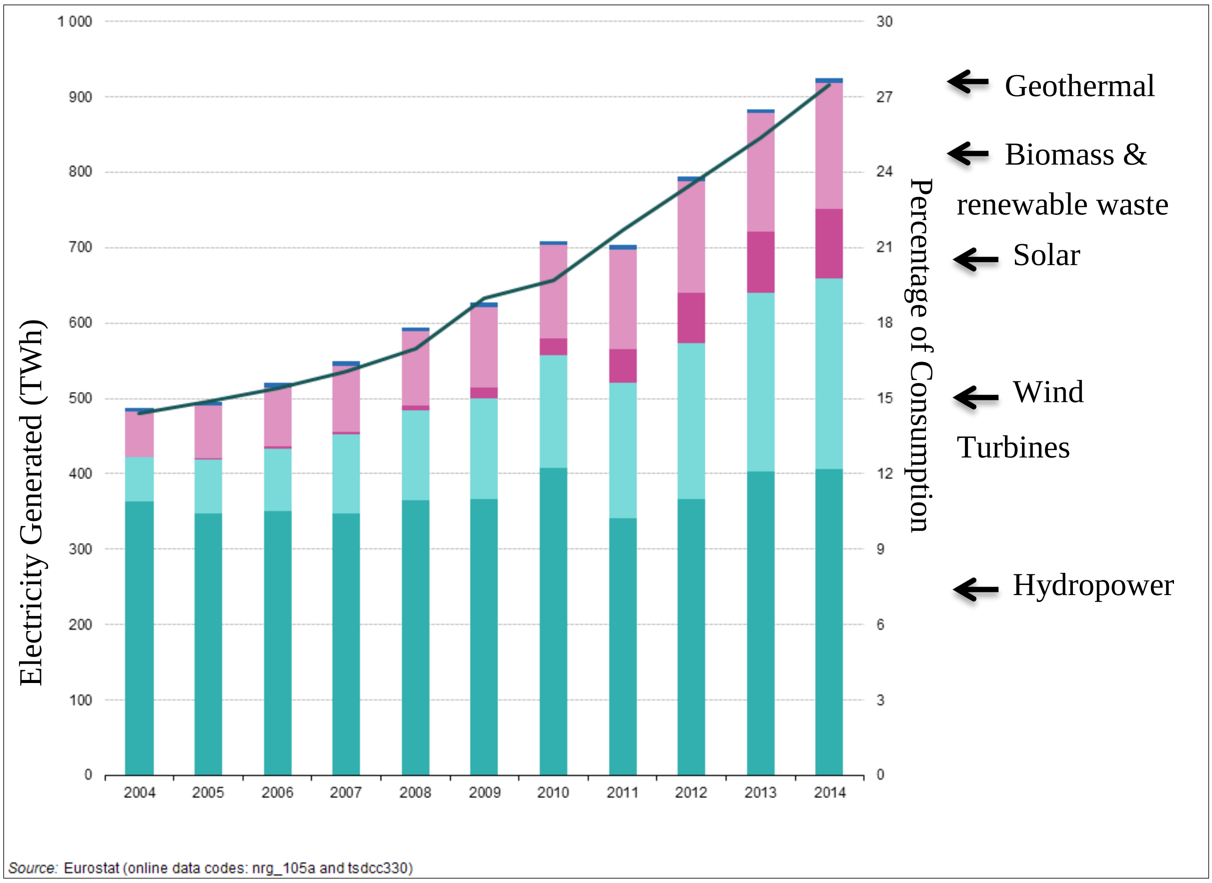

Figure 2-2 Electricity generated from renewable energy sources EU-28, 2004-2014

Source: Retrieved from: “http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Electricity_generated_from_renewable_energy_sources,_EU-28,_2004%E2%80%9314_YB16.png”

In 2014 almost 400 TWh of electricity from renewable energy sources is provided by Hydropower alone which accounts to almost 12% of the total energy consumption. It is observed that the share of energy from wind turbines has increased tremendously from 2004 to 2014. In 2014, electricity generated from wind power contributes almost 8% of the total electricity produced.

The table 2.2 gives the overview of share of electricity from renewable sources in gross electricity consumption in all the countries in EU in the period 2004-2014.

Table 2.2 Share of electricity from renewable sources in gross electricity consumption %

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
EU-28	14.4	14.9	15.4	16.1	17.0	19.0	19.7	21.7	23.5	25.4	27.5

Belgium	1.7	2.4	3.1	3.6	4.6	6.2	7.1	9.1	11.3	12.4	13.4
Bulgaria	9.1	9.3	9.3	9.4	10.0	11.3	12.7	12.9	16.1	18.9	18.9
Czech Republic	3.6	3.7	4	4.6	5.2	6.4	7.5	10.6	11.6	12.8	13.9
Denmark	23.8	24.6	24	25	25.9	28.3	32.7	35.9	38.7	43.1	48.5
Germany	9.4	10.5	11.8	13.6	15.1	17.4	18.1	20.9	23.6	25.3	28.2
Estonia	0.6	1.1	1.5	1.5	2.1	6.1	10.4	12.3	15.8	13	14.6
Ireland	6	72	8.7	10.4	11.2	13.4	14.5	17.2	19.5	20.8	22.7
Greece	7.8	8.2	8.9	9.3	9.6	11	12.3	13.8	16.4	21.2	21.9
Spain	19	19.1	20	21.7	23.7	27.8	29.8	31.6	33.5	36.7	37.8
France	13.8	13.7	14.1	14.3	14.4	15.1	14.8	16.3	16.4	16.8	18.3
Croatia	35.5	35.8	35.2	34	33.8	35.9	37.6	37.6	38.8	42.2	45.3
Italy	16.1	16.3	15.9	16	16.6	18.8	20.1	23.5	27.4	31.3	33.4
Cyprus	0	0	0	0.1	0.3	0.6	1.4	3.4	4.9	6.6	7.4
Latvia	46	43	40.4	38.6	38.7	41.9	42.1	44.7	44.9	48.8	51.1
Lithuania	3.6	3.8	4	4.7	4.9	5.9	7.4	9	10.9	13.1	13.7
Luxembourg	2.8	32	32	3.3	3.6	4.1	3.8	4.1	4.6	5.3	5.9
Hungary	2.2	4.4	3.5	4.2	5.3	7	7.1	6.4	6.1	6.6	7.3
Malta	0	0	0	0	0	0	0	0.5	1.1	1.6	3.3
Netherlands	4.4	6.3	6.5	6	7.5	9.1	9.6	9.8	10.4	10	10
Austria	61.8	62.4	62.4	64.6	65.2	67.8	65.7	66	66.5	68	70

Poland	2.1	2.7	3	3.5	4.4	5.8	6.6	8.2	10.7	10.7	12.4
Portugal	27.5	27.7	29.3	32.3	34.1	37.6	40.7	45.9	47.6	49.1	52.1
Romania	28.4	28.8	28.1	28.1	28.1	30.9	30.4	31.1	33.6	37.5	41.7
Slovenia	29.3	28.7	282	27.7	30	33.8	32.2	31	31.6	33.1	33.9
Slovak Republic	15.4	15.7	16.6	16.5	17	17.8	17.8	19.3	20.1	20.8	23
Finland	26.7	26.9	26.4	25.5	27.3	27.3	27.7	29.4	29.5	30.9	31.4
Sweden	51.2	50.9	51.8	53.2	53.6	58.3	56	59.9	60	61.8	63.3
United Kingdom	3.5	4.1	4.5	4.8	5.5	6.7	7.4	8.8	10.7	13.8	17.8
Iceland	93.1	94.9	93.5	113.7	90.8	92.9	92.4	93.9	95.4	96.7	97.1
Norway	97.3	96.8	100.2	98.5	99.6	104.7	97.9	105.5	104.4	106.9	109.6

Source: Retrieved from http://ec.europa.eu/eurostat/statistics-explained/images/c/c1/Share_of_electricity_from_renewable_sources_in_gross_electricity_consumption_%28%25%29.png

It can be observed from the table 2.2 that the total share of electricity from renewable sources in EU has increased from 14.4% in 2004 to 27.5% in 2014. It is also observed that among 28 countries, Norway contributes the most of all in electricity generation from renewable energy sources in gross electricity production of the European Union [7].

2.3 Driving Force for hydropower development

Recent trends show that many European countries are increasing the proportion of wind and solar power generation for the production of electricity [8]. The energy produced by such renewable resources is not possible to be stored in large amount which leads to increased need for energy storage to compensate for difference between production and consumption, known as balance power. Hydropower with storage reservoirs is the only form of renewable energy storage system presently in use. This has emphasized on the need to develop more storage hydropower schemes.

2.4 Status of Hydropower in Asia and Europe

2.4.1 Status of Hydropower in Asia

As published in the hydropower status report, 2016 by International hydropower association, South and Central Asian Region include a number of hubs for development of Hydropower such as Turkey, Tajikistan, Kyrgystan, the Himalayan region spanning Nepal, Bhutan and India's northernmost states. Harnessing the vast hydropower resources of Nepal and Bhutan is considered crucial in order to meet the rapidly growing energy demand of South Asia in a cost effective and environmentally sustainable manner. [9] Increased private sector involvement has been witnessed across the South and Central Asian region with a number of notable public-private partnerships which shows the new opportunities for Independent power producers [9].

The East Asia and Pacific region holds the largest share of global installed hydropower capacity. China alone accounts for almost one-third of global hydropower capacity. China's total installed hydropower capacity is estimated to be 319 GW by the end of 2015. It is observable that most of the developing countries have headed themselves in harnessing the clean renewable hydropower resources [9]. The table 2.3 and table 2.4 shows the total hydropower installed capacity of Asia [9].

Table 2.3 Hydropower Installed Capacity of South and Central Asia

Country	Total Installed Capacity including Pumped Storage(MW)	Pumped Storage (MW)	Generation (TWh)
Afghanistan	400	-	0.91
Bahrain	-	-	-
Bangladesh	230	-	1.49
Bhutan	1, 615	-	7. 7 8
India	51,494	4,786	124 . 65
Iran	11,19 6	1,040	13.79
Iraq	2,753	240	4.40

Israel	7	-	0.03
Jordan	12	-	0.06
Kazakhstan	2,260	-	7. 3 3
Kuwait	-	-	-
Kyrgyzstan	3,091	-	13. 81
Lebanon	221	-	0.66
Nepal	753	-	3.64
Oman	-	-	-
Pakistan	7, 2 6 4	-	31.18
Qatar	-	-	-
Russia	50,624	1, 360	16 0 .17
Saudi Arabia	-	-	-
Sri Lanka	1,624	-	5.12
Syria	1, 505	-	2.77
Tajikistan	5,19 0	-	17. 7 3
Turkey	25,886	-	66.90
Turkmenistan	1	-	-
United Arab Emirates	-	-	-
Uzbekistan	1,731	-	10. 31
Total	167,856	7,426	473

Source: Adapted from “Hydropower Status Report, 2016” by International Hydropower Association

It is observed that in South and Central Asia, the total hydropower installed capacity is 167,856 MW and out of them 7,426 MW is contribute by pumped storage plants. India and Russia remain the largest electricity producers from hydropower in this region.

Table 2.4 Hydropower Installed Capacity of East Asia and Pacific

Country	Total Installed Capacity including Pumped Storage(MW)	Pumped Storage (MW)	Generation (TWh)
American Samoa	-	-	-
Australia	8,790	74 0	13. 63
Brunei	-	-	-
Cambodia	1, 267	-	1.85
China	319, 370	23,060	1,126.4 0
Chinese Taipei	4,683	2,602	4.19
Cook Islands	-	-	-
Fiji	12 5	-	0.30
French Polynesia	47	-	0.29
Indonesia	5,258	-	13.74
Japan	49,905	27, 637	91. 27
Kiribati	-	-	-
Laos	4,16 8	-	18.70
Malaysia	5,472	-	11.98
Marshall Islands	-	-	-

Micronesia, Federated States Of	-	-	-
Mongolia	-	-	-
Myanmar	3,140	-	5.78
Nauru	-	-	-
New Caledonia	78	-	0.33
New Zealand	5,254	-	24.29
Niue	-	-	-
North Korea	5,000	-	13.14
Papua New Guinea	234	-	0.86
Philippines	4,235	685	9.95
Samoa	12	-	0.05
Singapore	-	-	-
Solomon Islands	-	-	-
South Korea	6,447	4,700	5.86
Thailand	4,510	1,000	11. 6 8
Timor-leste	-	-	-
Tonga	-	-	-
Tuvalu	-	-	-
Vanuatu	-	-	-
Vietnam	15 , 211	-	62.63

Wallis And Futuna	-	-	-
Total	443,207	60,424	1, 417

Source: Adapted from "Hydropower Status Report, 2016" by International Hydropower Association

In East Asia and Pacific, it is observed that the total hydropower production is 443,207 MW out of which 60,424 MW is contributed by pumped storage plants. China remains the leading hydro-electricity producer of this region with total hydro installed capacity of 319, 370 MW.

2.4.2 Status of Hydropower in Europe

Hydropower plays a major role to meet Europe's ambitious climate and energy goals. Wind and solar power is arising as future energy system of this continent. And it is sure to require sufficient flexibility, firm capacity and ability to balance the volatile generation over time horizons ranging from hours to several months. Hydropower helps in balancing the power in the European energy grid and the only form of electricity storage that is available on a large scale and at competitive cost is pumped storage hydropower. There is an estimated 218 GW of installed hydropower capacity in Europe, out of which more than 150 GW is contributed by storage and pumped storage stations. Most of the installed hydropower capacity is located in Scandinavia and the Alpine countries, while the unexploited hydropower potential is concentrated in Eastern Europe. The investment in Europe is primarily focused on pumped storage projects [9].

The table 2.5 shows the total hydropower installed capacity of Europe [9].

Table 2.5 Hydropower Installed Capacity of Europe

Country	Total Installed Capacity including Pumped Storage(MW)	Pumped Storage (MW)	Generation (TWh)
Åland Islands	-	-	-
Albania	1, 527	-	4.01
Andorra	45	-	0.10
Armenia	1, 249	-	2 .74

Austria	13,178	5,200	39.53
Azerbaijan	1,116	-	2.44
Belarus	33	-	0 .11
Belgium	1,427	1, 307	0.34
Bosnia and Herzegovina	2,504	420	6.50
Bulgaria	3,129	864	3.97
Croatia	2,141	293	6. 31
Cyprus	-	-	-
Czech Republic	2, 212	1,147	3.06
Denmark	9	-	0.02
Estonia	8	-	0.03
Faroe Islands	39	-	0.12
Finland	3,198	-	16. 54
France	25,397	6,985	57.30
Georgia	2,727	-	8.40
Germany	11,258	6,806	24.49
Gibraltar	-	-	-
Greece	3,396	699	5.59
Greenland	90	-	0.35
Hungary	56	-	0.23
Iceland	1,986	-	13. 65

Ireland	529	292	1.08
Italy	21, 880	7,555	44.75
Kosovo	36	-	0.13
Latvia	1, 576	-	3.18
Liechtenstein	-	-	-
Lithuania	876	760	0. 51
Luxembourg	1,13 4	1,10 0	0.09
Macedonia	674	-	1.19
Malta	-	-	-
Moldova	76	-	0.37
Montenegro	658	-	1.80
Netherlands	37	-	0.09
Norway	30,566	1, 351	139. 0 0
Poland	2,351	1,782	2.36
Portugal	5,902	1, 343	9.78
Romania	6,705	92	14.48
San Marino	-	-	-
Serbia	2,835	614	11. 5 0
Slovakia	2,522	916	3.79
Slovenia	1,479	180	4 .11
Spain	18, 561	5,268	32.01
Sweden	16,419	99	73.93

Switzerland	15, 635	1, 817	39.00
Ukraine	6,785	1, 315	11. 0 2
United Kingdom	4,443	2,74 4	8.65
Total	**218,404**	**50,949**	**599**

Source: Table Retrieved from “Hydropower Status Report, 2016” by International Hydropower Association

It is found that the total installed hydro capacity of EU countries is 218,404 MW out of which 50,949 MW is contributed by pumped storage plants. Norway remains the leading producer of hydro-electricity in this region with total installed capacity of 30,566 MW.

2.5 Status of Pumped Storage Hydropower in the World

Pumped storage is a cost-effective bulk energy storage system. Pumped hydro storage power plants represent approximately 99% of the world’s electrical energy storage capacity with over 150 GW [10]. Currently Japan is the worldwide leader in pumped storage hydropower but China is expanding its pumped storage hydropower plants quickly and is expected to surpass Japan in 2018. The table 2.6 shows the list of ten countries having the largest installed capacity pumped storage [10].

Table 2.6 Countries with Largest Installed capacity of Pumped Storage Plants

Country	Installed PHS Capacity (MW)
Japan	27,438
China	21,545
United States of America	20,858
Italy	7,071
Spain	6,889
Germany	6,388
France	5,894
India	5,072

Austria	4,808
South Korea	4,700

Source: Retrieved from "Pumped Storage Hydroelectric Power Plants: Issues and Applications, 2016" by Taczi, Istvan

2.6 Pumped Storage Hydropower in Europe

The development of pumped storage hydropower is accelerating in Europe with the increase in energy demand and balancing source of energy. The status of hydropower development along with pumped storage capacity in 2010 and projected status for 2020 [11] have been presented in table 2.7.

Table 2.7 Actual and projected total hydropower capacity and electricity generation in EU

Installed Capacity, (GW) and electricity generation (TWh)	2010		2020	
	Conventional (Large and small hydro)	PSH	Conventional (Large and small hydro)	PSH
GW	111.9	28.2	128.3	39.5
TWh	337.8	23.6	362.3	32.6

Source: adapted from "Assessment of renewable electricity generation by pumped storage power plants in EU Member States, 2013"

As stated in table 2.7, the capacity addition of conventional hydro-electricity is expected to increase in 2020 by 14.65% and addition of PSH is expected to be 40%. This also shows the emphasis given by EU to bulk storage system like pumped storage to address the variation between peak and off-peak power demand.

2.7 Pumped Storage Hydropower in Asia

Huizhou Pumped Storage Power Station (2,448 MW), Guangdong Pumped Storage Power Station (2,400), Okutataragi Pumped Storage Power Station (1,932 MW) are some of the biggest pumped storage power stations in Asia [12]. Japan with total PSH Installed Capacity of 27,438 MW is the largest PSH producer in Asia while China comes second with total PSH installed capacity 21545 MW by 2014 [10]. The need for energy is increasing rapidly in developing Asian countries and the demand for balancing energy source is felt as there is substantial difference between peak demand and off-peak demand. This scenario has led to planning and construction of pumped storage plants. Yet, it is seen that very few Asian countries have installed pumped storage plants to support their power system till date [13].

2.7.1 Development of Pumped storage power stations in China

The first PSH in China was put into operation in Gangnan, Pingshan County, Hebei Province on May 14, 1968. It is a mixed PSH with a pumped storage unit with the installed capacity of 11 MW. Its construction started the history of the PSH development in China. [14]. After the mid-1980s, the power network of China continually expanded with the rapid development of social economy, as the result of Chinese Reform and Opening. Thermal power dominated the power networks of Guangdong Province, North China and East China. The amount of hydropower that can be utilized in these regions is small as there are limited hydro resources in this region. But the power networks were facing problem with load regulation in absence of an appropriate economic measure. The power- shortage situation of the region changed from shortage of electric quantity to the deficiency of load regulation capacity. Consequently the construction of the PSH in power networks gradually became a compulsion to improve this problem. The total installed capacity of the PSH in China reached 21.83 GW by the end of 2014, which accounts for 1.6% of the national total in China. Up to 2020, the total installed capacity of the PSH will reach 70 GW [14].

3. Methodology

This thesis tries to illustrate the overview of the current conditions of energy consumption, energy production from renewable sources, hydropower, the demanding for balancing power in case of operation of wind power or other types of renewable energy in a grid system. Moreover this thesis analyses the case studies focused on PSHs in Europe and Asia and highlights the policies in development of PSH in EU and Asia. The thesis explores the recent trend of development of pumped storage hydroelectric plants in Europe and Asia. In this thesis, the comparison is made between the characteristics of PSH in operation in Asia and Europe from 2010 to 2017.

3.1 Pumped Storage Hydroelectric Plants in Asia

It is found that sixteen PSHs were constructed and put into operation in period of seven years from 2010 to 2017 [15]. The research work finds that out of sixteen PSHs, eight were installed in China. The details of PSHs in Asia taken into consideration along with their respective installed capacities are listed in table 3.1.

Table 3.1 Pumped Storage Hydroelectric Projects commissioned in Asia in time period 2010-2017

S.No.	Name of PSH	Rated Power (KW)	Location
1	Kyogoku Pumped Hydro Power Station (Unit 1)	200,000	Hokkaidō, Japan
2	Kyogoku Pumped Hydro Power Station (Unit 2)	200,000	Hokkaidō, Japan
3	Kazunogawa (No.4) Pump Expansion	400,000	Yamanashi, Japan
4	Yecheon Pumped Storage Power Plant	800,000	Gyeongsangbuk-do, South Korea
5	Kannagawa Hydropower Plant No.1, No. 2	940,000	Nagano, Japan
6	Xiangshuijian Pumped Storage Power Station	1,000,000	Anhui, China

7	Tehri Pumped Storage Hydroelectric Power Plant	1,000,000	Uttarakhand, India
8	Siah Bishe Pumped Storage Power Plant	1,040,000	Mazandaran, Iran
9	Xianyou Pumped Storage Power Station	1,200,000	Fujian, China
10	Baoquan Reservoir	1,200,000	XinXiang, China
11	Heimifeng Pumped Storage Power Station	1,200,000	Hunan, China
12	Pushihe Pumped Storage Power Station	1,200,000	Liaoning, China
13	Omarugawa Pumped Hydro Storage Station	1,200,000	Miyazaki, Japan
14	Hohhot Pumped Storage Power Station	1,224,000	Inner Mongolia, China
15	Xianju Pumped Storage Power Station	1,500,000	Zhejiang, China
16	Huizhou Pumped Storage Power Station	2,448,000	Guangdong, China

Source: http://www.energystorageexchange.org/projects/advanced_search

It is found that 16,752 MW of PSH is added to grids in Asia in the period 2010-2017. Most of the PSH plants are installed in China with total added capacity of 10,972 MW.

3.2 Pumped Storage Hydroelectric Plants in Europe

In Europe, seventeen PSHs are put into operation in the period 2010-2017 [15]. Out of them, four PSH were constructed in Austria. The details of PSHs in Europe taken into consideration along with their respective installed capacities are listed in table 3.2:

Table 3.2 Pumped Storage Hydroelectric Projects commissioned in Europe in time period2010-2017

S.No.	Name of PSH	Rated Power (KW)	Location
1	El Hierro Hydro-Wind Plant	11,300	Canary Islands, Spain
2	Baixo Sabor Jusante Pumped Hydro Station	36000	Portugal
3	Koralpe Pumped Storage Power Plant	50,000	Kärnten, Austria
4	Feldsee Pumped Storage Power Plant	140,000	Karnten, Austria
5	Waldeck I Pumped Hydro Power Plant	140000	Hesse, Germany
6	Baixo Sabor Montante Pumped Hydro Station - EDP	153000	Portugal
7	Avče Pumped Hydro Storage Plant	185,000	Slovenian Littoral, Slovenia
8	Salamonde II Pumped Hydro Station	211,000	Portugal
9	Foz Tua Pumped Hydro Station	259,000	Portugal
10	Reisseck II Pumped Storage Power Plant	430000	Carynthia, Austria
11	Limberg II Pumped Storage Power Station	480,000	Salzburg, Austria
12	Veytaux (FMHL+) Pumped Hydro Storage Power Plant	480,000	Montreux, Switzerland
13	Venda Nova III Pumped Hydro Station	736,000	Distrito de Braga, Portugal
14	Frades II Pumped Hydro Station - Voith	778,000	Portugal
15	Linthal 2015 (Linth-Limmern Expansion) Pumped Hydro Storage Power Plant	1,000,000	Glarus, Switzerland
16	Aguayo II Pumped Storage Power Plant	1,014,000	Cantabria, Spain

17	La Muela pumped-storage plant	2,000,000	Valancia, Spain

Source: http://www.energystorageexchange.org/projects/advanced_search

It is found that in the above mentioned period, 8103.3 MW of PSH capacity is added to grids in Europe.

3.3 Comparison of PSH development in Europe and Asia

In order to draw out the differences in patterns of PSH development in Europe and Asia, attempt has been made to compare annual addition of installed capacity of PSH in both continents. Moreover, comparison is made between unit cost of PSH construction taking PSH of similar capacity into consideration. Similarly, the major objectives of PSH installation with respect to power grid is compared taking the above mentioned PSHs into consideration. Lastly the PSH development policies of some of the representative countries of Europe and Asia are discussed to estimate the future trend of PSH development.

3.3.1 Annual Addition of PSH in grids in Europe and Asia

In order to compare the annual addition of PSH, the PSHs commissioned in the period 2010-2017 are grouped based on their year of commissioning and the total addition for each year in Europe and Asia was calculated and compared.

3.3.2 Cost of PSH construction in Europe and Asia

The unit cost of PSH development highly depends on a number of factors such as topography, geology and accessibility of the project area. The thesis has attempted to compare the unit cost of construction in PSHs in Europe and Asia commissioned in the period 2010-2017.

For the comparison of unit cost of installation of PSH in Europe and Asia, the projects with similar capacity are grouped together. The total cost of construction of individual PSHs are divided by their installed capacity to compute per-megawatt-cost of construction.

3.3.3 Use Cases of PSH in Europe and Asia

PSH contribute to the power grid in a number of ways. Based on the requirement of grid, PSH are set to perform particular tasks. This thesis work has attempted to investigate the general trend of use of PSHs in the grids in European and Asian countries. The investigation is carried out to classify the PSHs based on the following use cases in the grid [16]:

a) Electric Energy Time Shift

b) Electric Supply Capacity
c) Load Following (Tertiary Balancing)
d) Electric Supply Reserve Capacity- Spinning
e) Frequency Regulation
f) Volatage Support
g) Renewable Energy Time Shift
h) Black Start
i) Renewables Capacity Firming

3.3.4 Ownership of PSHs in Europe and Asia

Comparison is made to see whether the public institution owns the PSH or there is participation of private sector. The investigation is carried out to determine the general trend of ownership of each of the above mentioned PSH projects. This comparison greatly reflects the policies undertaken by the countries for development of PSHs.

3.3.5 Policies for development of PSHs in Europe and Asia

The thesis research gives the overview of obstructions/ difficulties faced, historical changes in policies and current policies undertaken by some representing countries of Europe and Asia.

4. Data Analysis and Result

4.1 Annual Addition of PSH in grids in Europe and Asia

In the period of 2010-2017 total of 8,103.3 MW of Pumped Storage Capacity was added to the grids in European countries while in the same period total of 16,752 MW was added to the grids in Asia [15]. This shows there is high demand of balancing power in grids in Asia and Europe. Moreover, the installed capacity of new PSH in Asia in the same period is double the installed capacity of Europe.

The comparative study of total annual addition of PSHs in Europe and Asia in time period 2010-2017 are presented in figure 4-1:

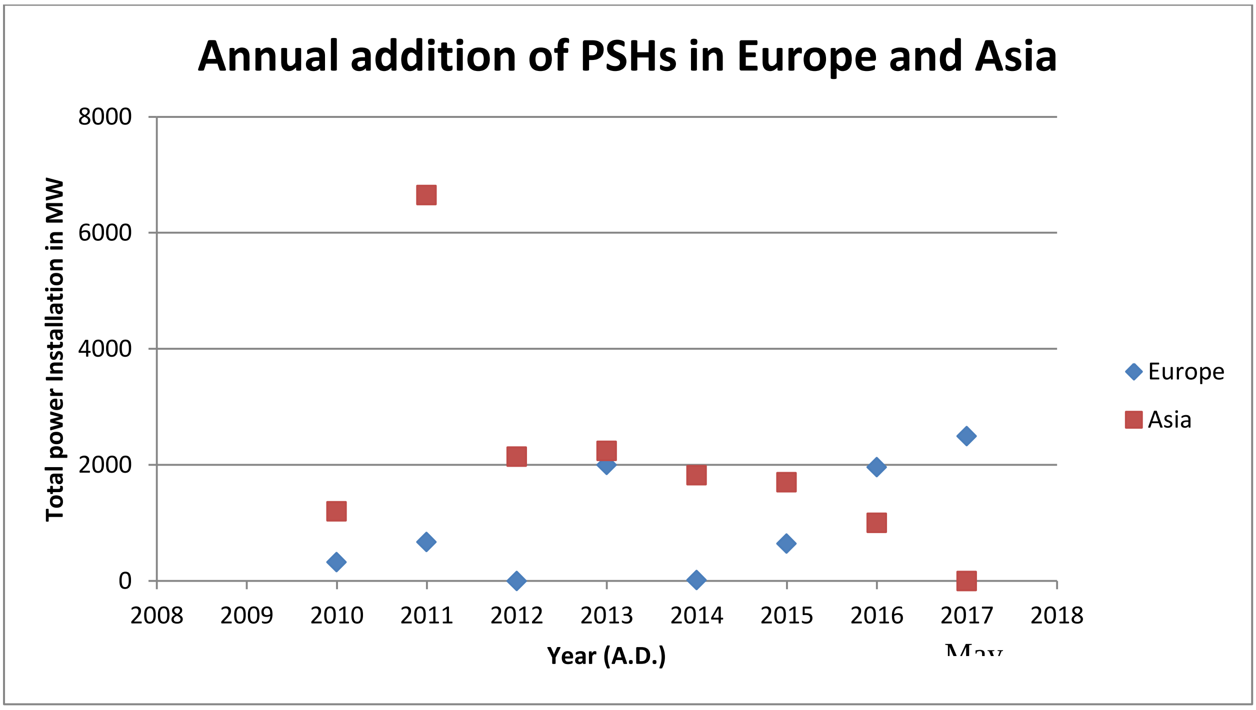

Figure 4-1 Annual addition of Pumped Storage Hydro capacity in Europe and Asia

It is found from figure 4-1 that in average, the yearly addition of PSH capacity is higher in case of Asia than in Europe. The difference in addition is very high in 2011 where 6,648 MW was added to grids in Asia while 670 MW was added to grids in Europe.

4.2 Cost of PSH construction in Europe and Asia

The unit cost of construction of PSHs in Europe and Asia for different range of installed capacity are compared and plotted as shown in figure 4-2:

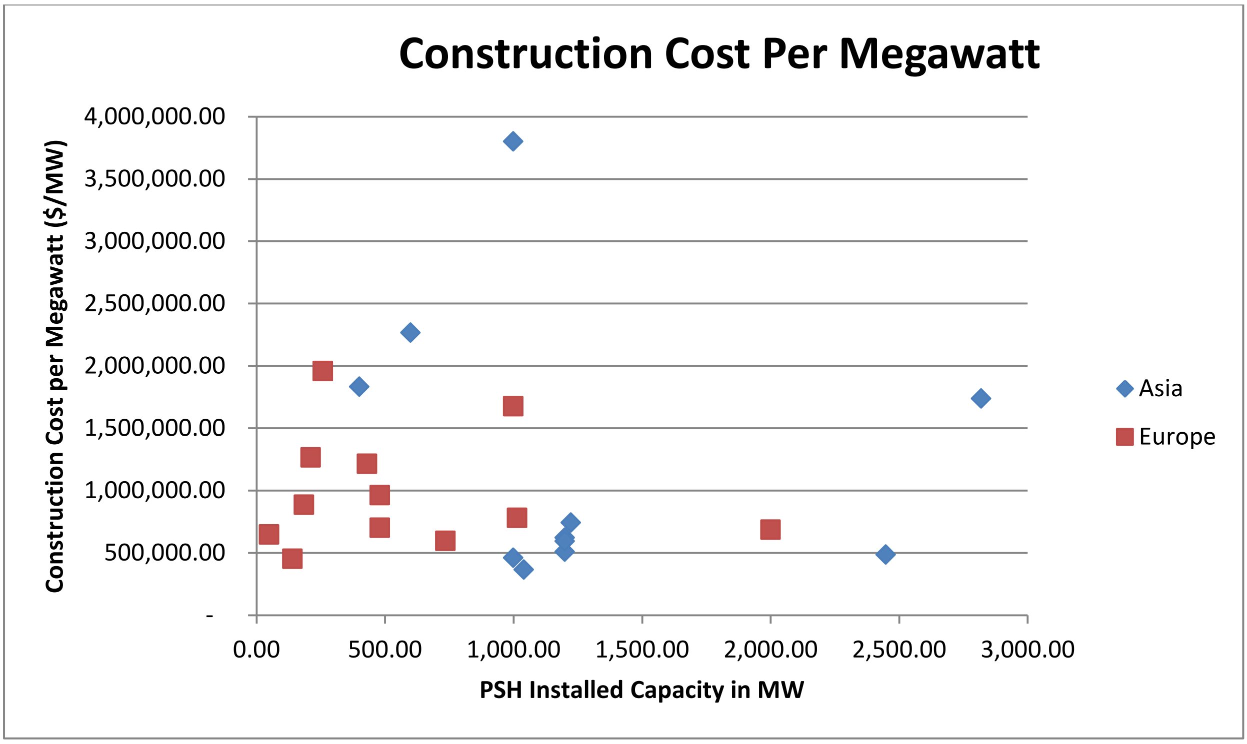

Figure 4-2 Unit cost of Construction ($ per MW) of PSHs in Europe and Asia

It is found that overall unit cost of construction is almost similar for Europe and Asia. Unit cost for few projects in Asia are found exceptionally high.

4.3 Use Cases of PSH in Europe and Asia

This thesis work has attempted to investigate the general use cases of PSH in countries of Europe and Asia. The use cases are highlighted below:

Use Cases of PSH in Asia

The use cases of PSHs in Asia are categorized based on the primary, secondary, tertiary objectives of development of the particular PSH [15] and their intended role in the power grid. The details are given in the table 4.1.

Table 4.1 Use Cases of Pumped Storage Hydroelectric Plants in Asia

PSH Project	Rated Power (Kw)	Location	Use Case 1	Use Case 2	Use Case 3	Use Case 4	Use Case 5
Kyogoku Pumped Hydro Power Station (Unit 1)	200,000	Japan	Electric Energy Time	Electric Supply Capacity			

			Shift				
Kyogoku Pumped Hydro Power Station (Unit 2)	200,000	Hokkaidō, Japan	Electric Energy Time Shift	Electric Supply Capacity			
Kazunogawa (No.4) Pump Expansion	400,000	Yamanashi, Japan	Electric Energy Time Shift	Electric Supply Capacity			
Yecheon Pumped Storage Power Plant	800,000	Gyeongsangbuk-do, South Korea	Electric Energy Time Shift	Electric Supply Capacity			
Kannagawa Hydropower Plant No.1, No. 2	940,000	Nagano, Japan	Black Start	Electric Energy Time Shift	Electric Supply Capacity	Electric Supply Reserve Capacity - Spinning	Frequency Regulation
Xiangshuijian Pumped Storage Power Station	1,000,000	Anhui, China	Electric Energy Time Shift	Electric Supply Capacity	Load Following (Tertiary Balancing)	Electric Supply Reserve Capacity - Spinni	Frequency Regulation

						ng	
Tehri Pumped Storage Hydroelectric Power Plant	1,000,000	Uttarakhand, India	Electric Energy Time Shift	Electric Supply Capacity			
Siah Bishe Pumped Storage Power Plant	1,040,000	Mazandaran, Iran	Electric Energy Time Shift	Electric Supply Capacity	Load Following (Tertiary Balancing)		
Xianyou Pumped Storage Power Station	1,200,000	Fujian, China	Electric Energy Time Shift	Electric Supply Capacity	Electric Supply Reserve Capacity - Spinning	Frequency Regulation	Load Following (Tertiary Balancing)
Baoquan Reservoir	1,200,000	XinXiang, China	Electric Energy Time Shift				
Heimifeng Pumped Storage Power Station	1,200,000	Hunan, China	Electric Energy Time Shift	Electric Supply Reserve Capacity - Spinning			
Pushihe Pumped Storage Power	1,200,000	Liaoning, China	Electric Energy	Electric Supply	Frequency	Voltage	

Station			Time Shift	Reserve Capacity - Spinning	Regulation	Support	
Omarugawa Pumped Hydro Storage Station	1,200,000	Miyazaki, Japan	Electric Energy Time Shift	Electric Supply Capacity	Frequency Regulation		
Hohhot Pumped Storage Power Station - Alstom / GE	1,224,000	Inner Mongolia, China	Electric Energy Time Shift	Electric Supply Reserve Capacity - Spinning	Frequency Regulation	Renewables Energy Time Shift	
Xianju Pumped Storage Power Station	1,500,000	Zhejiang, China	Electric Energy Time Shift	Electric Supply Capacity	Frequency Regulation		
Huizhou Pumped Storage Power Station	2,448,000	Guangdong, China	Electric Energy Time Shift	Electric Supply Reserve Capacity - Spinning	Frequency Regulation		

The above information is graphically represented and analyzed to visualize the trend of use cases of PSH in Asia in the figure 4-3.

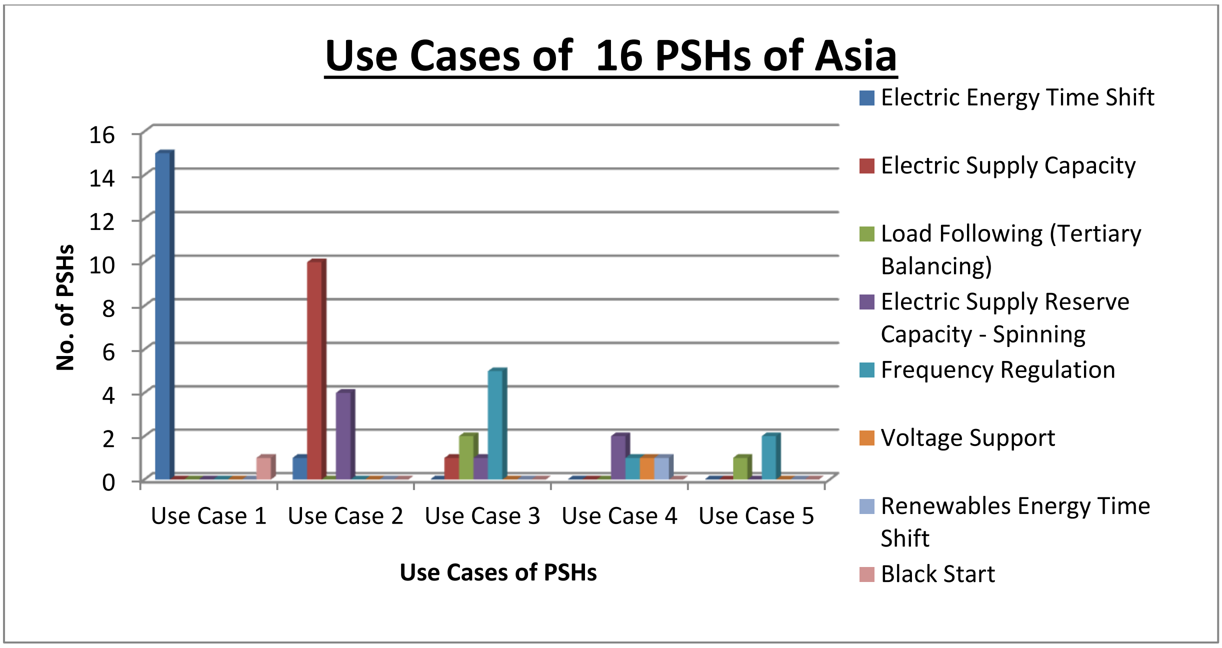

Figure 4-3 Use Cases of Pumped Storage Hydroelectric Plants (Commissioned in 2010-2017) in Asia

It is observed from the above information that out of sixteen PSHs in Asia commissioned between 2010-2017 fifteen are primarily used for electric energy time shift. Fifteen PSHs serve secondary purpose out of which ten PSHs are used for enhancing the electric supply capacity. Furthermore, nine projects are used for tertiary purpose and out of them seven serve the purpose of frequency regulation in the grid. Similarly, five out of sixteen PSHs serve fourth purpose and three out of sixteen serve even fifth purpose. Minority of projects are used for tertiary balancing, renewable energy time shift, voltage support or black start.

Use Cases of PSH in Europe

The use cases of PSHs in Europe are categorized based on the primary objective of development of the particular PSH [15]. Details are presented in table 4.2.

Table 4.2 Use Cases of Pumped Storage Hydroelectric Plants in Europe

PSH Project	Rated Power (Kw)	Location	Use Case 1	Use Case 2	Use Case 3	Use Case 4	Use Case 5
El Hierro Hydro-Wind Plant	11,300	Canary Islands, Spain	Renewables Capacity Firming	Renewables Energy Time	Electric Supply Capacity		

				Shift			
Baixo Sabor Jusante Pumped Hydro Station	36000	Portugal	Electric Energy Time Shift	Electric Supply Capacity			
Koralpe Pumped Storage Power Plant	50,000	Kärnten, Austria	Electric Energy Time Shift	Electric Supply Capacity			
Feldsee Pumped Storage Power Plant	140,000	Karnten, Austria	Electric Energy Time Shift	Electric Supply Capacity	Renewables Energy Time Shift	Load Following (Tertiary Balancing)	
Waldeck I Pumped Hydro Power Plant	140000	Hesse, Germany	Electric Energy Time Shift	Electric Supply Capacity			
Baixo Sabor Montante Pumped Hydro Station - EDP	153000	Portugal	Electric Energy Time Shift	Electric Supply Capacity			
Avče Pumped Hydro Storage Plant	185,000	Slovenian Littoral, Slovenia	Electric Energy Time Shift	Electric Supply Capacity			
Salamonde II Pumped Hydro Station	211,000	Portugal	Electric Supply Capacity	Electric Energy Time			

				Shift			
Foz Tua Pumped Hydro Station	259,000	Portugal	Electric Energy Time Shift	Electric Supply Capacity			
Reisseck II Pumped Storage Power Plant	430000	Carynthia, Austria	Electric Energy Time Shift	Electric Supply Capacity			
Limberg II Pumped Storage Power Station	480,000	Salzburg, Austria	Electric Energy Time Shift	Electric Supply Capacity	Electric Supply Reserve Capacity - Spinning	Frequency Regulation	Voltage Support
Veytaux (FMHL+) Pumped Hydro Storage Power Plant	480,000	Montreux, Switzerland	Electric Energy Time Shift	Electric Supply Capacity			
Venda Nova III Pumped Hydro Station	736,000	Distrito de Braga, Portugal	Electric Energy Time Shift	Electric Supply Capacity			
Frades II Pumped Hydro Station - Voith	778,000	Portugal	Electric Energy Time Shift	Electric Supply Capacity			
Linthal 2015 (Linth-Limmern Expansion) Pumped Hydro	1,000,000	Glarus, Switzerland	Electric Energy Time Shift	Electric Supply Capacity			

Storage Power Plant							
Aguayo II Pumped Storage Power Plant	1,014,000	Cantabria, Spain	Electric Energy Time Shift	Electric Supply Capacity	Electric Supply Reserve Capacity - Spinning	Renewables Energy Time Shift	
La Muela pumped-storage plant	2,000,000	Valancia, Spain	Renewables Capacity Firming				

The above information is graphically represented and analyzed to visualize the trend of use cases of PSH in Europe in the figure 4-4:

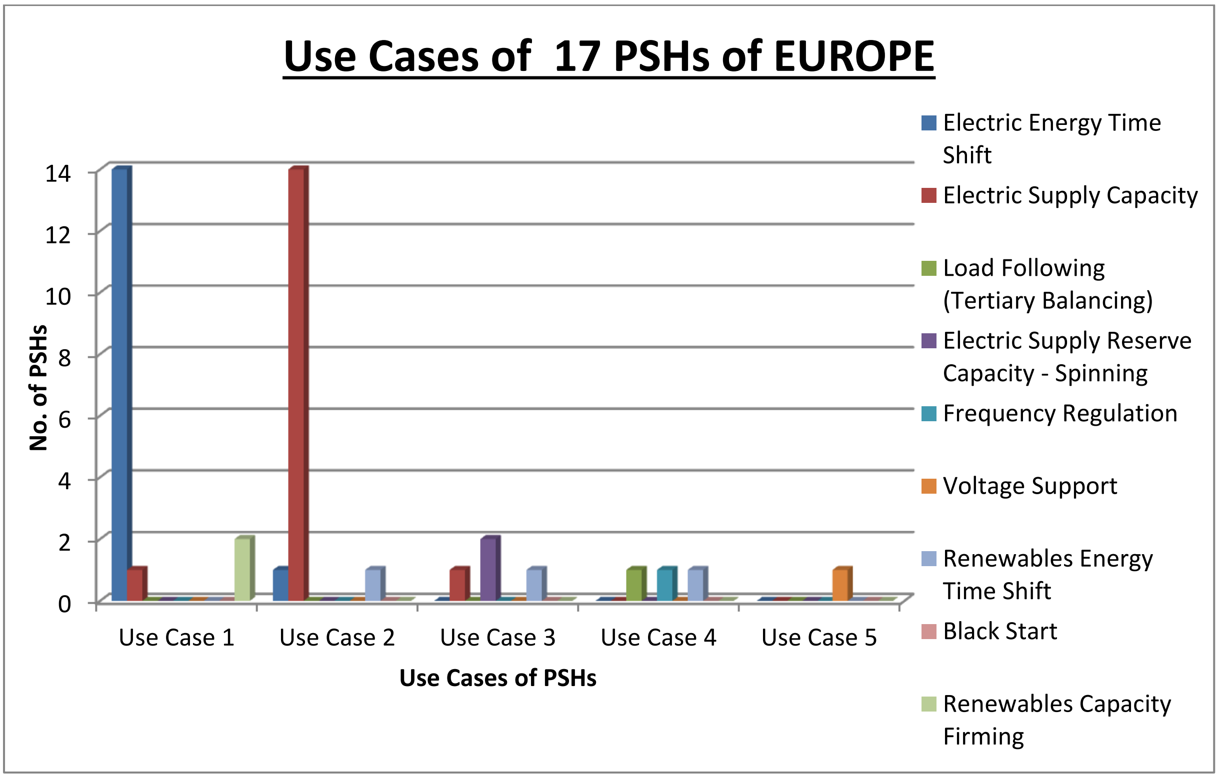

Figure 4-4 Use Cases of Pumped Storage Hydroelectric Plants (Commissioned in 2010-2017) in Europe

It is observed from the above information that out of seventeen PSHs in Europe commissioned between 2010-2017, fourteen are primarily used for electric energy time shift. sixteen PSHs also serve secondary purpose out of which fourteen PSHs are used for enhancing the electric supply capacity. Furthermore, four Projects are used for tertiary purpose and out of them two serve the purpose of electric supply reserve capacity in the grid. Similarly, three out of seventeen PSHs serve fourth purpose and one out of seventeen serve even fifth purpose. Minority of projects serve purpose of tertiary balancing, frequency regulation, renewable energy time shift, voltage support, renewables capacity firming or black start.

From the analysis of PSHs developed in time period 2010-2017, it is seen that PSHs in Asia and Europe are primarily constructed for time shifting of electric energy, which means, storing energy in time of low demand and using it to produce energy during period of high demand. As seen from figures 4-3 and 4-4, secondarily, PSH serve for electric supply capacity enhancement in both continents. Electric supply reserve capacity-spinning seems to be the third purpose of PSH development in Europe, while frequency regulation is the next purpose of PSH development in Asia.

4.4 Ownership of PSHs in Europe and Asia

It is observed that the participation of private sector is not satisfactory in the construction of PSH projects, which may be due to high level of technological complexities and financial risks associated with the development of PSH projects [15]. As the history of PSH development is quite older in case of Europe than in Asia, relatively more private sector participation is spotted in Europe. In Asia, particularly China and developing countries like India, almost all the PSH plants are owned and operated by Public sector [15].

4.5 Policies for development of PSHs in Europe and Asia

4.5.1 Policies undertaken in Europe

Policies undertaken by the respective government greatly influences the development of PSH. As stated by Sufang Zhang [17] in Germany, restrictions on the sizes of reservoir were the most obvious constraint for PSH preventing them from adequately supporting excessive renewable generation over very long periods of time. In Croatia, every services provided by PSH to the electricity systems were not adequately rewarded by the electricity market. Moreover, regulated level of curtailment of excess renewable energy hindered operation of PSH [17]. PSH and other generating devices with the same characteristics are treated in the same way as in the European Network Code on requirements for grid connection [10]. It is clarified in the renewable energy directive that electricity produced from PSH units should not be considered as renewable energy. However, the directive has emphasized on the need to support the integration of energy from renewable sources into the transmission and distribution grid [10]. Currently, No particular investment framework exists for PSH. In most of the EU countries PSH pays double fees (tariffs) for network access as PSH acts as an electricity consumer and electricity generator based on its mode of operation. In the same time, some Transmission Service Operators (TSO) charge nothing for the PSH's role as electricity consumer and others recognize it as a renewable based generator [10]. It is very essential for largely interconnected grids such as in EU countries, to apply common rules regarding transmission access fees and use of system fees for electricity storage systems to avoid situations like deployment of an electricity storage facility in one country with favorable rules to provide services in next country with less favorable rules. No EU legislation exists to regulate this issue and PSHs are treated as they fit in the local market circumstances. Differences in policy across national markets create distortions impacting access and related costs of energy from PSH in neighboring markets [10].

4.5.2 Policies undertaken in Asia

Except some developed countries, PSH is still a new concept to most of the countries in Asia. Countries face a number of unwanted circumstances in planning, construction and operation of PSH. In India, the deficit of off peak power for pumping in almost all regional grids highly constrained PSH operation [17]. In China, most of the PSH plants before 2000 were constructed under a generation-based tariff which was unattractive to investors. This tariff regime did not fully reflect the value of PSH plants and hence the costs of PSH plants could not be fully compensated. The structural reforms to electrical power sector of 2002 changed the context for the construction, operation and tariff of PSH plants and as a result, in 2013, the cumulative operation capacity in China reached 21.55 GW from 5.6 GW in 2000 [17]. Some particular characteristics of PSH that can be used for financial sustaining are not yet paid enough attention [17].

4.5.3 Recommendation for Policies Changes

It is often argued that it is uneconomic to build profitable PSH under the prevailing legal and regulatory framework [10]. Moreover market uncertainties have negative impact on profitability of PSH. A number of modifications need to be done in existing policies to address issues related to financial sustainability of PSH project.

First and foremost, PSH systems should be paid for the ancillary services they provide such as the ability to provide superior regulating reserves (fast response), load balancing ability and voltage control in the grid. Expanding and inter linking the regional grid connections so as to incorporate the advantages of PSH fully can be a second measure [17]. A next effective policy change can be the establishment of time-of-day tariffs for generators in countries where they lack this system [17]. Using time-of-day generator tariffs instead of uniform tariff irrespective of time helps storage systems like PSH to operate in a more financially sustainable way. Pumped Storage System supports environmental safeguard by reducing necessity of fuel-based generators with high carbon emission during peak load time. Hence strict environmental regulations need to be made flexible for construction of PSH taking into consideration, the positive effects of clean energy in the environment produced from PSH.

5. Discussion

This thesis research highlights in the beginning, the increasing demand of energy in Europe. The above research shows that the share of renewable energy in the energy market is increasing in Europe. Based on the data for the time period 2004-2014 as presented in this research, after hydro energy, wind energy is emerging as major renewable energy source in EU followed by Solar energy. The energy harnessed from solar and wind turbines are highly intermittent and there is no proper efficient bulk storage system to store such huge amount of energy to use during period of high demand except pumped-hydro storage system. This has led to immediate need to construct more pumped storage plants. This thesis has highlighted the targets set by countries in Europe and Asia to increase capacity of pumped storage system.

As presented in Hydropower Status Report 2016, total of 50,949 MW of pumped storage capacity has been added to European grids and many new are under construction. In the same time, in Asia, 67,850 MW of pumped storage capacity has been added.

The thesis research has met its general objectives of understanding the status of energy consumption and development of renewable energy sources in EU countries. It is found in Hydropower Status Report, 2016 that total of 611,063 MW of hydro-energy has been installed in Asia while total of 218,404 MW of hydro-energy has been installed in Europe in same time. Moreover after a thorough research it is found that a total of 69, 850 MW of pumped storage capacity has been added to grids in Asia and 50,949 MW of pumped storage capacity has been added in Europe. Even though the overall PSH capacity in Asia seems to be more, this is mostly concentrated in few countries such as Japan, China, South Korea, India and Russia. Hence it does not give the true status of pumped storage development of all countries in Asia.

In order to address the specific objective of thesis research, the characteristics of pumped storage hydropower commissioned in the present decade 2010-2017 in Europe and Asia have been compared. It is observed that the average annual addition of PSH installed capacity is slightly more in case of Asia than in Europe in the period 2010-2017. The increased imbalance in power grids, especially in China, and the policies undertaken by China for PSH development greatly influenced addition of PSH in Asia. In the period 2010-2017 total of 16,752 MW of PSH was added in Asia and again more than half of it was installed in China alone. Similarly in the same period, 8103.3 MW of PSH capacity was added. In case of Europe, the construction of PSH projects is not concentrated in few countries unlike China.

Moreover, the comparison of unit cost of PSH development in Europe and Asia does not give a clear distinction, yet, in average, the cost of PSH development seems slightly lower in Europe. Cost of some of the projects considered in Asia are found exceptionally high which may be due to topographical, geological or location factors but the investigation of the reason for high cost is not carried out in this research work.

In most cases, primary objective of PSH development is electric energy time shift in case of Europe and Asia. Electric Supply Capacity remains the major secondary application. It is observed that frequency regulation of the power system is next major application for Asian PSHs while PSHs in Europe serve third purpose of electric supply reserve capacity. The multiple functions are solely dependent on the requirements of the grid of the particular place and the technology used by the PSH plant. Only the general trend of multiple use cases have been analyzed in this research.

The major reason for state-ownership of PSHs in most countries in Asia may be the inadequacy in policies for profitable operation of PSH. While in case of European countries, since the history of PSH development is longer and a lot has been researched and formulated to ensure profitability, significant participation of private sector is seen.

As the next specific objective of the research, the researcher has investigated on the prevailing policies related to PSH in some of the countries in Europe and Asia. It is found that the prevailing policies in Europe are not enough in most of the countries to ensure profitable operation of PSH. In Europe, market specific policies regarding PSH have made investment risky. No clear distinction between PSH and other renewable energy systems is the next hindrance. It is found that in most of the Asian countries PSH is still a new concept and hence no specific policies are found for PSH development. In China, policies were changed a number of times to ensure profitable operation of PSH. A number of recommendations as described earlier in this research are necessary to help development of PSH.

6. Conclusions

The purpose of this thesis is to research on the status of energy consumption, development of renewable energy sources, development of hydropower and pumped storage hydropower in Europe and Asia. Specific objective include in-depth study of PSH, comparative study of PSH in Europe and Asia and analysis of policies undertaken for PSH development. The objectives of this research work are achieved through a series of literature reviews and investigations.

At first the thesis highlights the status of energy consumption and development of renewable sources in Europe. At second stage, status of hydropower and pumped storage hydropower in Europe and Asia are compared. Furthermore, for detailed comparison of PSH in Europe and Asia, seventeen PSHs from Europe and sixteen PSHs from Asia commissioned in the present decade (2010-2017) are taken. Comparison is made in a number of categories and differences are highlighted. Furthermore policies in European and Asian countries regarding PSH development are discussed. Thus, the thesis has been successful in researching its pre-defined objectives.

7. Further Research

Further research can be done taking into consideration a large number of PSHs that were in operation before the period mentioned in the thesis and under construction or scheduled to be construction in near future which will provide more clear picture in the differences in the overall trend of PSH development in Europe and Asia. Moreover, Further research work can be on the PSH projects that were shut down as a result of existing policies and their inabilities to address issues related to PSH. Similarly, in-depth research can be conducted on the causes of variation in unit cost of construction in different PSH of similar capacity in Europe and Asia.

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