Hydro Electricity and Storage Capabilities in Norway – can they be useful for Europe?

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Abstract

The electricity supply of Norway is nearly 100% based on hydro power. More than half the production capacity is from storage reservoirs, primarily established for coping with annual fluctuation in inflow to the reservoirs and seasonal variation in power demand.

Existing, mainly high–voltage direct - current cable, connections with mainly thermal power systems in neighbouring countries, are basically built for hourly power exchange (day – night), and for handling the power balance in dry or wet years, with energy shortage or surplus respectively. In a normal year the system is approximately in balance.

Within the economic, political and technical framework of the present regime, the conditions for a substantial exploitation of Norway's hydro power resources as a storage system to deal with the large fluctuations in production from intermittent wind and/or solar energy is presented.

Based on technological and economic facts, one of the main conclusions may be that some relatively modest expansion of the exchange capacity between Norway and the Continent may be realised in the near future, but will most probably only make a relatively small contribution to the challenges caused by increasing shares of intermittent power supply to the power system in Northern Europe.

On a larger scale power exchange as a solution to the challenge caused by fluctuating input from renewable sources most probably will have to compete with the installation of more gas fired power.

1. Introduction

The electricity supply of Norway is close to 100% based on hydro power. Some gas and biomass (waste) fired power, together limited to about 1 000 MW, is included in the total installed power capacity of about 29 000 MW onshore. The offshore sector is mainly supplied by local gas turbines with some heat recovery.

Electricity makes up for close to half of all onshore domestic energy consumption, which has as a consequence that the renewable share of total Norway's energy consumption onshore is about 60%.

As a large share of the electricity consumption is for domestic heating, with maximum demand during winter months when normally there is little inflow to the hydro reservoirs, large hydro power reservoirs are necessary. More than half the production capacity is accordingly from storage reservoirs.

These reservoirs are also important in handling the large annual variation of precipitation and inflow. The difference in energy production capacity from an extremely wet year to an extremely dry year is from more than 160 TWh down to below 100 TWh.

The largest reservoir (energy content), Blåsjø in the Ulla-Førre hydro-power complex, figure 1, may store up to 7.8 TWh.

Existing connections with thermally based power systems in neighbouring countries are built for both hourly power exchange (day – night), and for handling the power balance in dry or wet years. In a normal year the Norwegian system is at the present approximately in balance.

Figure 1: Energy storage reservoir

Hydro power is in principle an intermittent renewable source like solar or wind, but in contrast to wind or solar generation, the energy storage (dam) is often, but not always, a natural and integrated part of a hydro electric installation.

In addition to the storage possibility, the reservoir based hydro power system is well suited for short time power regulation, as the output may be regulated on short notice.

The hydro power storage system is currently exploited as a regulator in connection with varying wind power generation in the Nordic system. The cable connection between Norway and Denmark is an important power link when Danish wind power production experiences large fluctuations in power output.

Extending this capacity, and making a large scale exchange between Norway and Northern Europe possible in a future with increasing share of intermittent wind (and solar) power, might seem to be a natural development.

2. The Norwegian hydro power system

Hydro power installations may normally be categorized in two different types, the so-called "run of river" and the "reservoir" type. While the first one is characterized by a low head with usually relatively high flow volumes and low degree of control on power output, the reservoir type normally has a high head and within reasonable limits full control of power output. This makes the reservoir type suitable to adjust output to fit production to demand and to (higher) prices. These stations are often built with an installation that results in a relatively short utilisation period (annual energy production divided by installed capacity).

Historically the power installation has been optimized with regard to economy and energy output. As a consequence of this the Norwegian power system so far has had more than sufficient power capacity (MW) to meet the highest peak demand. The reservoir type represents ca. 60% of installed capacity in Norway (in TWh). Some reservoir type installations are built as back-up for dry years with reservoirs which may have a filling period (with normal precipitation) up to 3 to 4 years.

The average annual electricity production, and consumption, is about 123 TWh. The possible economically exploitable potential with present price expectations is up to 200 TWh. The potential is, in addition to price scenarios, also very much dependent on environmental protection policies. With the present policy, about 40 TWh is protected from commercial development.

To put things in a North European perspective it may be mentioned that if absolutely all precipitation falling on the Norwegian mainland should be exploited (strictly theoretical) for hydro power production, the annual production would be approximately equivalent to the present total German electricity consumption, which is about 600 TWh.

New hydro capacity presently being developed is typically relatively small scale projects with little or no storage capacity. Together with some expansion in installed wind power, this has as a main consequence that the installed power capacity, and to some lesser extent also the storage capability, may be further stressed in the future.

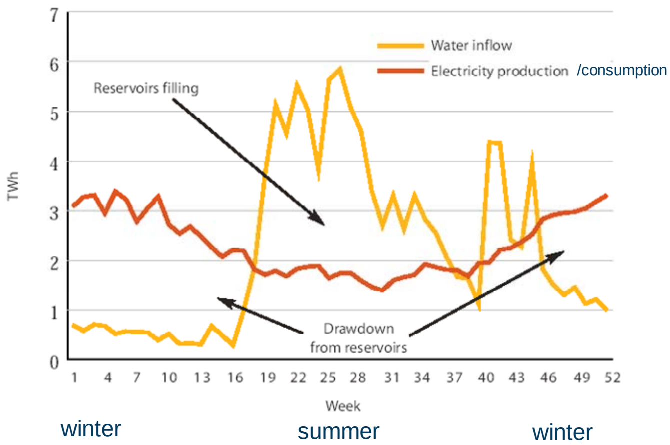

Figure 2: Storage reservoirs to adapt production to demand

In addition to the reservoir capacity available to cope with the challenge of handling variations in precipitation and demand, an exchange capacity with neighbouring countries is available. The total exchange capacity is about 5 000 MW. The highest exchange capacity is with Sweden (about 3 000 MW), which has an installed production mix of hydro and nuclear power. Experience has shown that all too often there is a correlation between abnormal precipitation situations in the two countries, which then implies that in dry years not much import to Norway may be expected from Sweden.

The exchange capacity with typically thermal production areas as Denmark and The Netherlands is therefore of special importance. The present total capacity through a limited number of subsea HVDC cables is about 1 700 MW. In addition to a systematic power exchange with export to the thermal systems during high demand (and prices) at daytime, and import at low demand at night, the power flow is strongly influenced by situations in which the hydro systems experiences extreme dry or wet periods.

The total installed power capacity in Norway is approximately 29 000 MW. Normally about 26 000 MW would be available during winter months, and the maximum demand recorded (2010) is 24 000 MW. See figure 3.

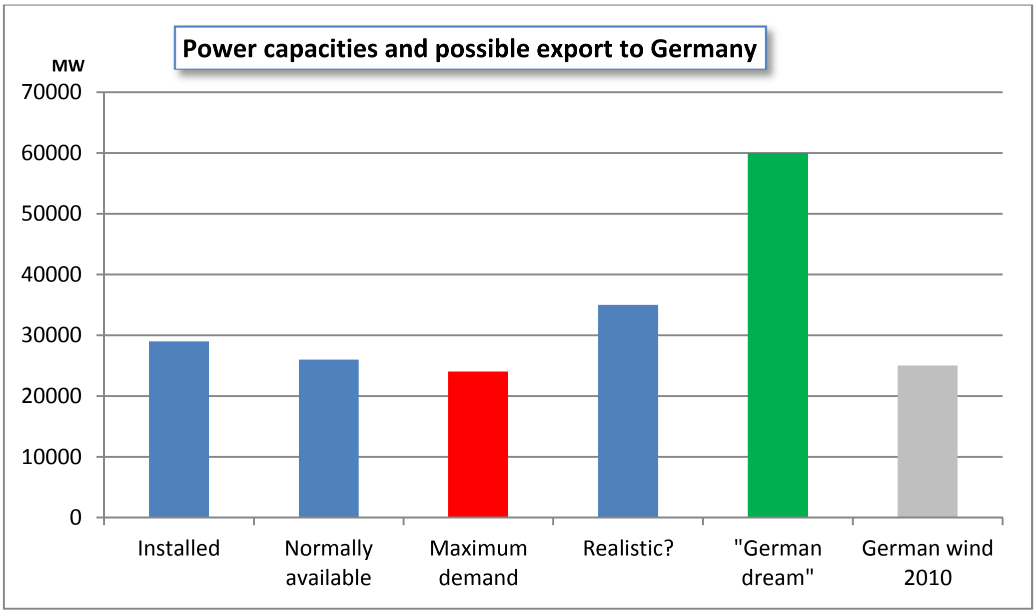

Figure 3: Power capacities – MW

In this context it is of interest to note that the present (2010) installed wind power capacity in Germany is of the same order of magnitude as the total installed hydro power capacity of Norway.

From the data presented above it may be concluded that the realization of a substantial and reliable power exchange with Germany, through new HVDC cable connections, will make new power (MW) installations in Norway necessary. Energy may then be stored in Norway by importing power when there is a surplus of wind power available and reducing the hydro power production. The stored water in the reservoirs may then later be utilized during periods with low wind power production. As a result the utilization time of the hydro system will be reduced, and the hydrological system (reservoir and a possible downstream river system) will experience larger and faster fluctuations.

Based on preliminary studies it has been assumed that the power capacity may be expanded to somewhere between 33 000 and 35 000 MW without unacceptable consequences regarding the environment (Indicated as a “realistic?” in figure 3). This would be sufficient to cover the increased demand related to the realization of approximately 3 to 5 new HVDC subsea cable connections. The possible controversial influences on the environment are caused by necessary reinforcements of onshore power lines and changes in the hydraulic system, rivers and reservoirs.

3. Large scale intermittent renewable energy challenges the power systems

In the following the focus will be limited to Northern Europe and specifically to the German system, as it is to be expected that the influence of intermittent power production from solar and wind will be the most pronounced in this country. This limitation is further motivated by the proximity to Norway and actual plans for developing new direct power exchange capacity between these two countries.

As the wind is not always blowing, and the sun is not always shining, the power input from the renewables solar and wind to the supply system will by nature be intermittent. This has as a consequence that the so-called utilization time (also called capacity factor) will be relatively low compared with what may be obtained with nuclear or fossil fuelled power sources. The utilization time is defined as the annual number of hours at full capacity necessary to supply the total annual supply of energy from the actual energy source.

Electricity may normally not be stored as such on a scale that can correct the balance between supply from these renewable sources and demand. The challenge to the power system is further increased by the fact that the German wind and solar power are both characterized by having, in an international comparison, very low utilization factors. This is illustrated in figure 4 below.

While the installed capacity of renewables, according to some scenarios being presented, may constitute more than 50 % of the total German power capacity to be expected in 2020, the energy contribution on average will make up for only 25 to 30 percent of the assumed total.

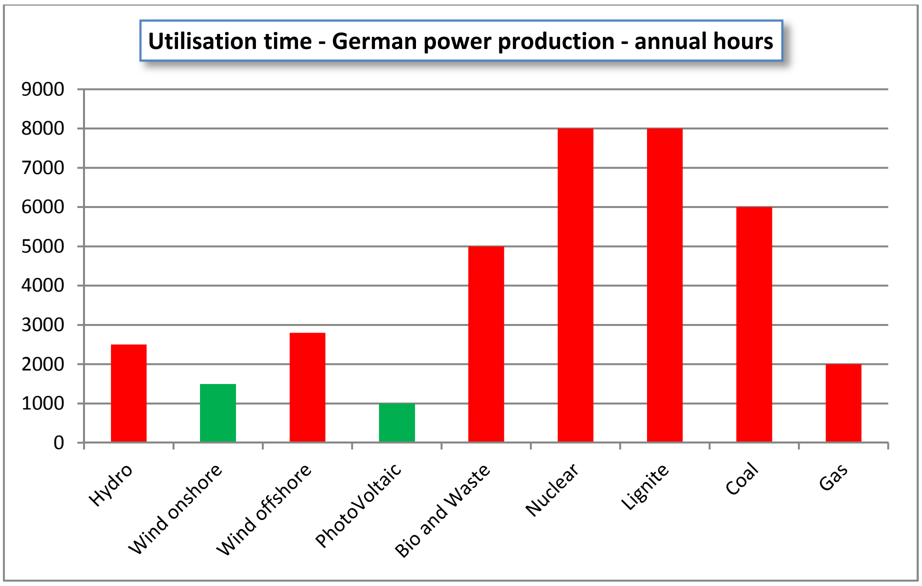

Figure 4: Experienced utilisation time of German power production

In the periods when power from the renewable sources are negligible, and demand is high, energy has to be supplied from other sources. This is a challenge that has proven manageable as long as the share of wind or solar in the system is limited. Power input from other sources is then adjusted to balance the system. If the share of these intermittent sources is increased to around 50 % or more of the total installed capacity, other solutions may prove necessary. During periods when the input from renewables is higher than demand, energy storage is needed if all power produced is to be utilized. This simplified and principal description of the challenge may to some extent be influenced by exchange possibilities with other power systems with different characteristics.

With the present German wind power capacity of more than 25 000 MW, one will find that the difference in energy output from this source (maximum – minimum) over a 48 hours period may amount to about 1000 GWh. This variation in energy input may then be compared with the total installed (hydro pumped) electrical storage capacity presently available in Germany, which is about 50 GWh.

The total storage capacity in the Norwegian hydro system is about 84 000 GWh. As an immediate reflection it might seem more realistic to get the necessary energy storage capacity by a power exchange with Norway then to expand the German energy storage capacity with a factor of more than 20. It is of interest to note that the installed German pumped power (MW) capacity is close to 8 000 MW (about a factor 3 less than installed wind capacity), which may indicate that the capacity (MW) problem is less of a challenge than solving the energy storage capacity problem.

However, the exploitation of a power exchange with the Norwegian hydro power system as a solution is connected with a number of limitations and challenges. The greatest challenge might be to create the necessary infrastructure and capacities, such as new subsea HVDC cables between the two systems and onshore line connections, in addition to the extra generator capacity needed in Norway.

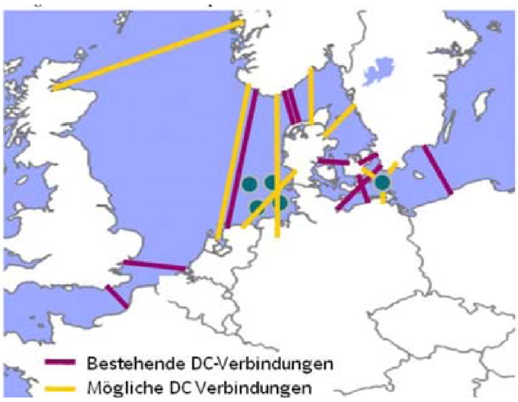

Figure 5: Power exchange connections between the Continent and Norway - Sweden

According to Hohmeyer [1]; "Europe needs 200 000 MW back up by quick response hydro power (PSP - Pumped Storage Plant) to cope with the effect of 100% renewable power in 2050. Part of this capacity, approximately 60 000 MW may be supplied from Norway".

As has been earlier described, this capacity is far from being available from the Norwegian system, neither as installed generator capacity, nor as transmission capacity from the power plant and cross border into Germany. Assuming that the total system shall be as reliable at any time as the present system, this means that the extra exchange capacity more or less has to come in addition to the present system. Operating the Norwegian power system at triple capacity, 60 000 MW, in addition to the present installed close to 30 000 MW, will have dramatic effects on the environment. Both the hydrological system connected to the power installations, and the introduction of increased transmission capacity, may turn out to be highly controversial.

As already mentioned, figure 4, according to evaluations made by Norwegian authorities and some power companies, a realistic scenario seems to be that the total installed power capacity in the southern part of Norway may be increased by an expansion in existing power stations to somewhere between 33 000 and 35 000 MW. This may be realised without any substantial negative environmental consequences.

Within an assumed technical potential, hereby stressing the system closer to an assumed limit and accepting some negative environmental effects, the capacity might be further increased to somewhere between 10.000 and 20.000 MW. [2]

It is relevant to note that the possible realisation of one, or possibly two, new subsea cable connections with a total capacity of 2 800 MW between Norway and Germany have been in the planning for a number of years. Different opinions regarding the economics, ownership issues and consequences for the local (Norwegian) electricity prices, have been some of the points of national discussion. Expanding this capacity substantially will most probably be a great challenge.

4. The power market and economical realities

The Norwegian power market is integrated in the Nordic NordPool market, which is linked via connections through mainly Sweden and Denmark (limited extent also to The Netherlands – via the Nor Ned cable) with also the German power market. Within the capacity constraints of the present system, power is traded on a regular day to day basis.

The general rule is that electricity will be exchanged if the marginal price difference between two market areas is sufficiently large. The natural energy flow will be from an area with low prices to the area with the highest price. Expressed in a more common language, Norway will experience export when Norwegian power prices are low (lower than the receiving area), and have import when prices are high. In other words, export at high prices will normally not be the case. Large scale, continuous, export of hydro power from Norway will have to compete with the marginal production cost of available Continental thermal power. Profitability in large scale investments in new hydro (or wind) power intended for export, in an area that experiences surplus of installed capacity, may be difficult to achieve.

As the marginal cost of renewables are more or less zero, these producers will always be in production, if and when these resources are available. Therefore they will normally not determine the power pool prices. The pool price is normally assumed to be the marginal cost of the last MW produced necessary to match the demand. In spite of the fact that solar power normally is the most expensive source, due to the high capital cost, the solar power will never determine the power price in the market (except when input from renewables are in excess of the actual demand, and prices may be forced to zero!).

So far the power exchange between Norway and the thermally dominated market areas Denmark and The Netherlands has experienced profitability for the trading partners due to the following:

- <u>Short term exchange – balancing power.</u>
  During normal inflow conditions there may be export of power at high prices during daytime, and import during low load and low prices at night. In addition there is some exchange caused by short time variation in Danish output of wind power, import at low prices and export from Norway at high prices.
  In principle this is an exchange that may be close to neutral (generally a limited net export is experienced) in energy supply, and is more a kind of balancing power supply and a power capacity exchange. The effect of this exchange is that the Norwegian power system produces the same amount of energy, but during a shorter time period. Due to the price fluctuations and differences, the Norwegian power producers are indirectly paid for the balancing service.

- <u>Longer term exchange – balancing the energy supply</u>.
  Larger scale export or import might take place during extreme inflow conditions to the hydro power system. Export will be normal when inflow is much higher than normal (and often combined with low consumption, as wet periods are often also mild periods), and import during dry periods with low inflow to the reservoirs. Again the Norwegian export will be at low prices, and import at higher prices. Typically it has been experienced that these relatively long exchange periods may have duration in the order of one year. The diagram in figure 6 shows the experienced exchange between Norway and neighbouring countries during the period 1997 to 2011, NVE [3].

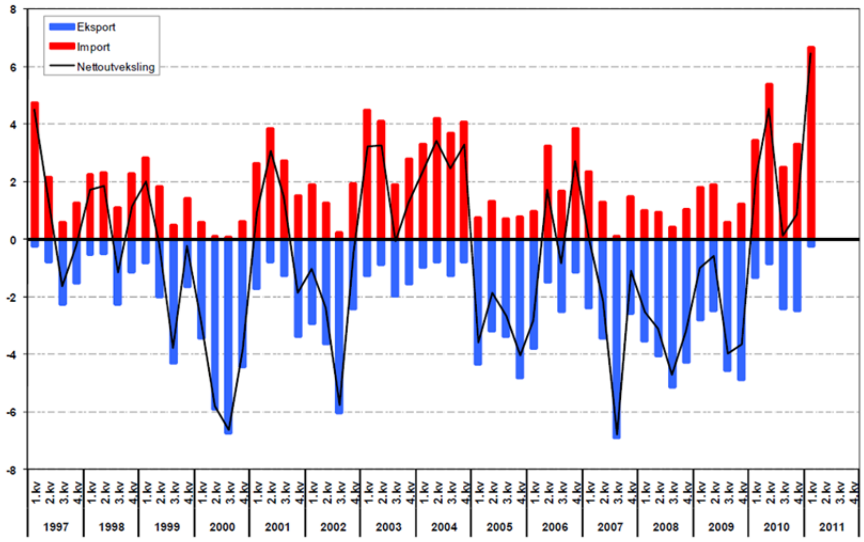

Figure 6: Quarterly total Norwegian power exchanges

A power exchange as described does not directly utilise any pumped storage as such. The hydro resources are being exploited during a shorter production period, resulting in a reduced utilisation time of the installations. The economic incentive to install more power capacity in a system with hydro reservoirs is to allow a producer to shift a limited production (by inflow) from periods with low prices to periods with higher prices.

Investments in pumping capacity might be realised if expected price differences in the local market (NordPool) are large enough to make this profitable. With an expected total energy efficiency of about 80 % for pumped storage, the necessary Norwegian <u>systematic</u> day/night price variations have to increase substantially before investments in pumping capacity may be profitable. See figure 7. The figure shows the average price structure in Germany and the south of Norway during the years 2002 to 2008. The Norwegian price variations are small, due to the dominating (sufficient), and easy to regulate, hydro power. German prices increase during peak hours, as sources with higher marginal cost are needed to cover peak demand.

Utilising pumping capacity to exploit the possibility to buy at normally lower prices during summer, or during longer wet periods, and store the energy to winter or dry periods with higher prices could possibly make investments profitable. A critical factor in this scenario is that the producer must have sufficient free storage capacity, and that the statistical risk of an overflow and subsequent loss during future unpredictable precipitation is limited.

The profitability of new exchange capacity between Norway and Germany, based on systematic price differences between the two markets, has been looked into by Aasheim [4].

The total costs of a new HVDC subsea cable is estimated to 1400 Million Euros. With a capacity of 1400 MW this is close to 1 M€/MW (Source: Statnett.no). If reinforcements in power stations are required, investments in the order of 0.3 €/MW has to be added. Investments in grid reinforcements are not included. (1€ is set to 8 NOK)

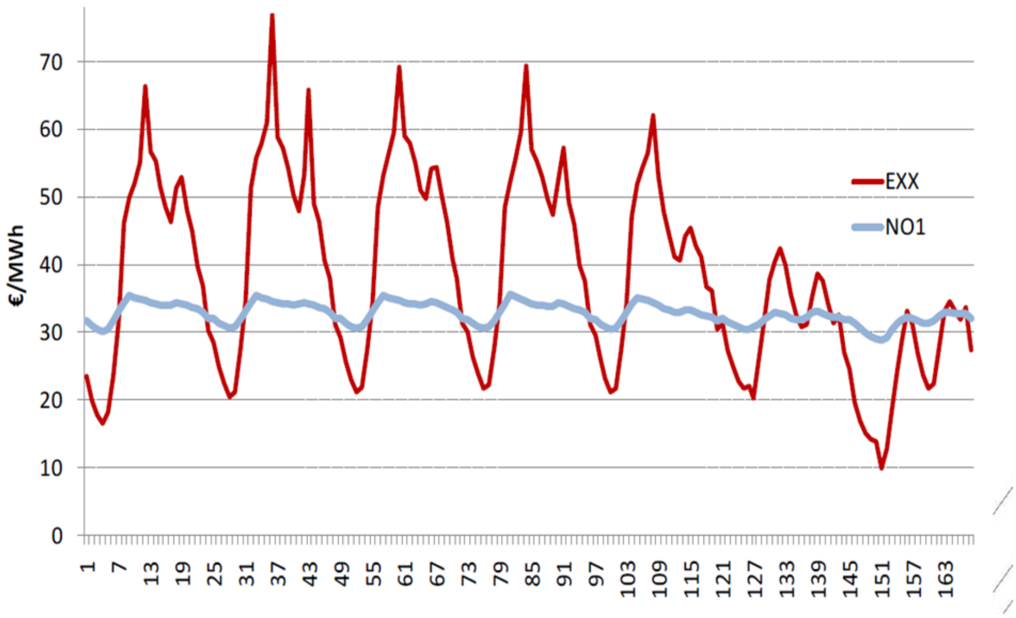

Figure 7: Average weekly and daily price variations Norway - Germany

Economical analysis based solely on the (historical) average price differences and investment cost referred to above, concludes that the profitability of a new cable and exchange capacity is uncertain. If increased exchange capacity makes investments in new capacity, both power and grid, necessary, - the economics becomes questionable.

On the other hand it is quite possible that future prices may differ more, especially if, or when, more wind power is connected to the system. In addition there are business opportunities in the already described exchange based on longer term variations caused by abnormal inflow conditions to the hydro power system.

Price differences between the two markets, Germany and Norway, as illustrated in figure 7, are caused by the fact that there are bottlenecks in the power transmission system. If a sufficiently large exchange capacity should be realised, the prices differences will be reduced, and the power exchange between the market areas will no longer be profitable. An exchange capacity increase limited to a few thousand MWs is not expected to make any significant reduction in the price differences.

However, increasing the capacity to a level that might be able to handle a substantial part of the challenge caused by the variations in output from German wind and solar power, as estimated earlier, will most probably lead to significantly reduced price differences. This could imply that investments in such an exchange capacity will not be realised based on normal economic incentives as these are experienced in the present power market.

5. What are the alternatives to cross border power exchange?

A German power market where large part of nuclear and coal fired base load is replaced by intermittent wind and solar power will need to have a back-up during low output from these sources. In addition the possible storage of surplus renewable power during periods where the power input is higher than demand would be very attractive.

A power exchange with the Norwegian, and to some extent also Swedish, hydro power represents one of a number of options. If large scale exchange should be developed, the total cost per capacity unit, as shown earlier, excluding central grid reinforcements, will be in the order of 1.3 M€/MW.

Another option is to rely on gas fired power as a back-up. (The storage of energy during surplus periods will then not be taken care of.) Gas fired power plants are the least expensive alternative per unit of power, and even if one should decide to go for a combined cycle plant with efficiency close to 60 %, the investments cost will be in the order of 0.8 M€/MW. A single cycle unit with lower efficiency would cost substantially less. Gas grid connection is not included. For the gas option the gas purchase contract and possible local gas storage possibilities will certainly have an influence on the total cost related to this solution.

Another technical option is to develop local energy storage in Germany; at least theoretically this could be new pumped storage capacity or compressed air storage. Restricting this evaluation to pumped storage (hydro) only, the assumed cost (strongly dependent on local conditions) seems to be in the order of 1.3 M€/MW, Vennemann et.al. [5]

As may be noticed this is comparable to the exchange solution, subsea cable plus power station reinforcements. Most probably the greatest obstacle for realising the local option are caused by natural, physical restrictions, such as finding an acceptable location which may provide the necessary reservoir(s) at sufficient difference in height. As mentioned earlier, it might seem that it is less challenging to solve the power problem (instantaneous and short term capacity – i.e. MWs) than finding a solution to the energy supply problem during periods with low renewable power input.

6. Conclusions

Whether the challenge posed by introducing a substantial amount of intermittent renewable energy sources to the power market in northern continental Europe can be solved by a power exchange with hydro power based Norway or not does not seem to have any clear answer.

Based on pure technical considerations, with Norway’s about 85 TWh of storage capacity, a power exchange could theoretically make a substantial contribution. In practice the Norwegian resources might certainly be useful, but most probably the capacity will be limited to a level that most probably only will make a relatively small impact in comparison to the energy and power capacity that seems to be required.

Technical, practical, political and commercial limitations will be caused by a number of factors, such as:

- The operation of the Norwegian power system will be strongly influenced by a power exchange activity sufficiently large to handle a substantial part of the fluctuations in a power system in Northern Europe dominated by intermittent renewable power sources. Large scale power exchange may cause a significant negative influence of environmental character, both on the hydrological system and the necessity of extensive grid reinforcements.

- Large scale power exchange, in the order of 20 000 to 60 000 MW, will make large investments in power station capacity, national grid and HVDC subsea cables, necessary. Within some reasonable constraints in the power capacity level the cost benefit analysis may prove favorable, but this may not be the case when going to a larger scale.
- As long as the power exchange is to be based on the present market system, there will be a strong element of economical unpredictability and risk. Too much capacity may reduce the price differences between the markets, and thereby the profit implicit in the trading activity between them.
- Building a back-up capacity for missing input from renewable wind and solar by investments in gas fired power capacity seems to be the most economic and low risk solution. This will certainly appear favorable as long as most of the renewable power capacity is limited and the input from wind and solar can be absorbed in the market, also during periods with high input and low load.

Summing up, it might be concluded that some contribution to the energy storage challenge might be realized, but it seems rather unlikely that a power exchange with Norway can contribute with more than only a fraction of what seems to be needed in a possible future dominated by intermittent renewable power sources.

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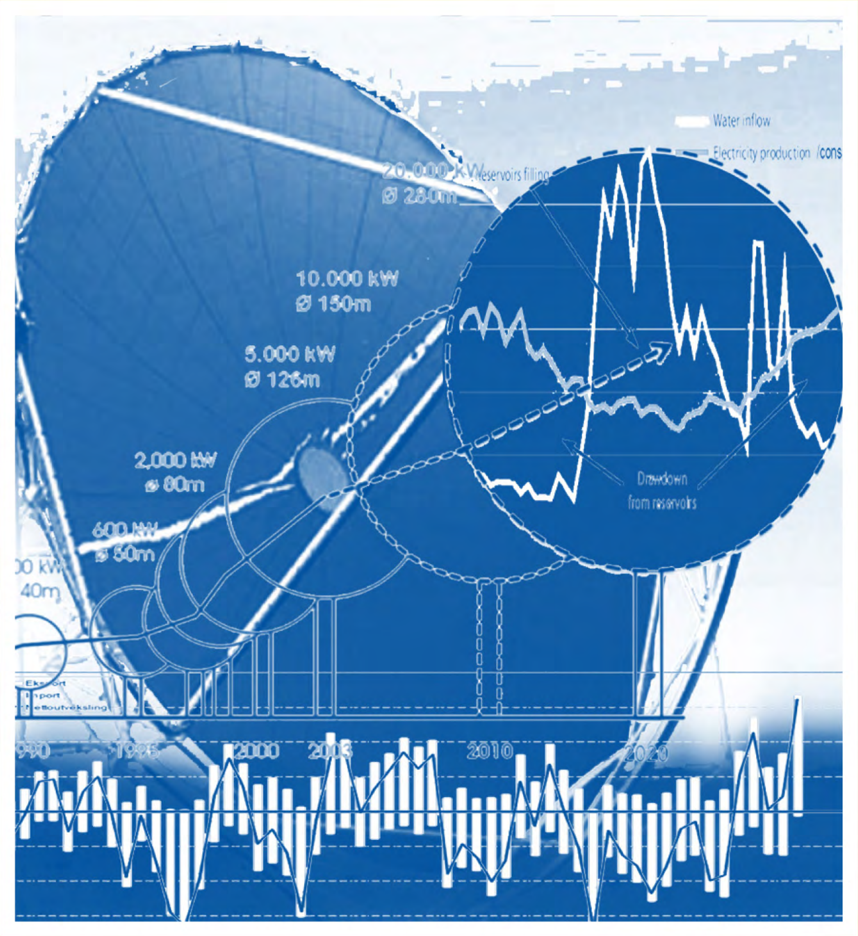

Energiewende

Aspekte, Optionen, Herausforderungen

Vorträge auf der DPG-Frühjahrstagung in Berlin 2012

Herausgegeben von Hardo Bruhns

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Arbeitskreis Energie in der Deutschen Physikalischen Gesellschaft

Berlin, 26. bis 28. März 2012

Programmgestaltung und Herausgeber: Hardo Bruhns

September 2012

Frühjahrstagung des Arbeitskreises Energie in der Deutschen Physikalischen Gesellschaft Berlin, 26. bis 28. März 2012

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Düsseldorf, im September 2012 Hardo Bruhns