Enhancement of the environmental performance of power and heat supply by the combined use of wind driven energy, natural gas and district heating

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INTRODUCTION

The transition to a more sustainable energy supply and consumption system involves the large scale introduction of wind and solar based electricity generation, the production of gas and electricity by biomass, vehicles driven by electricity or biogas, and energy conservation. The context, however, is a new society without a loss of quality of life with respect to warming, heating, cooling, electricity, communications, food, consumer goods, amusement, travelling. This involves even higher requirements to the capacity, reliability and availability of energy, especially gas and electricity.

Modern society's natural gas and the electricity systems seems to fulfil these requirements to a large extent, but the full change-over to sustainable and societal acceptable sources may violate their performances. The natural gas production, transmission and distribution system is very robust with momentary unlimited capacity at its sources and capacity restrictions only by its pipelines. The capacity of gas pipelines in terms of energy transmission is, by the way, a magnitude larger than electricity transmission lines or distribution cables with similar functions.

The gas system has a large inherent storage capacity (line pack) and additional storage is technically feasible. The electricity system is characterised by its incapability to store electric energy as such. A rather complicated machinery is needed to generate electricity at the proper moment in the proper quantities. It becomes even more complex by the introduction of volatile and uncontrollable energy sources of a sustainable nature.

Production, transmission and distribution of natural gas is rather energy-efficient and only leakage losses are a relevant factor, especially due to the fact that methane is a 23 times stronger greenhouse gas than CO_2. As a consequence of the laws of thermodynamics, the upgrading of heat (fossil fuel, nuclear, biomass, geothermal, solar thermal) to electricity goes hand in hand with a substantial waste of energy, but the energy-efficiency of high voltage transmission and medium voltage distribution is rather high (overall 95%).

With the electricity system as a reference, the complementary roles of gas and electricity will be highlighted, with an emphasis on the need for gas to enable the energy transition.

1. VOLATILE ELECTRIC POWER GENERATION

A number of renewable power sources can be characterized by their hardly controllable and predictable electricity output, especially wind energy driven generators. It cannot be denied that some stochastic patterns can be recognized and a certain level of short term predictability can be achieved, as well as that control by curtailment is possible, but compared to conventional power sources the controllability is poor.

As such, for the electric power system, electricity produced by wind energy converters can be seen as negative load. Load in a larger network can be treated in a stochastic way, thus giving some degree of predictability. It also forces the power sources to ramp up their output or reduce it in line with the load patterns, usually in a diurnal rhythm. Some incidents may lead to sudden deviations from the normal pattern, like broadcasting of football matches or a need for air conditioning, though system operators recognise such impacts on the load well in advance and prepare their generators to ramp up in due time. The less repetitive pattern of the negative load from the wind mill driven generators can be superimposed upon the load pattern and treated, to a certain extent, in a similar way.

Photovoltaic energy supply is increasing drastically. To the ambitious 20-20-20 objectives of the European Union the installed capacity of solar electricity power will increase from 20 GW in 2011 to almost 60 GW in 2020 [1][2]. The energy production will be some per cent of the total amount. More than wind energy the diurnal and seasonal pattern of solar energy can be predicted. In that sense it is better comparable with a load pattern; i.e. a negative load pattern.

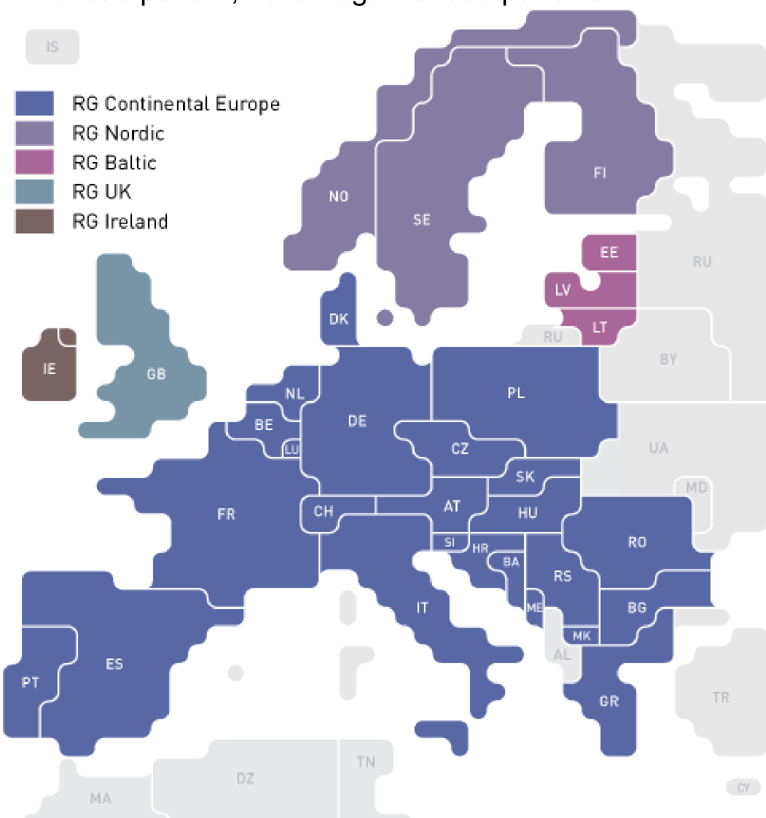

Figure 1 the Regio Groups in Europe with each a synchronous system [3]
Synchronous means that the whole network is operated at exactly
the same power frequency; i.e. close to 50 Hz

In a huge electric power system as the European interconnected synchronous system, covering almost all continental European countries (figure 1: RG Continental Europe) with an installed capacity of over 700 GW the peak load is about 400 GW. The difference of 300 GW consists of unavailable power due to maintenance and outages as well as power reserved for system services (cold stand-by, hot stand-by, spinning reserves) and other margins. In addition, about half of the 300 GW is variable and unpredictable power generation, partly due to (small) combined heat and power generation plants, run of river hydro plants and roughly 100 GW due to wind and solar energy. So, when running, up to 25% of the peak load is covered by wind energy driven generators and alike, a percentage that still can be handled by the European synchronous system [21].

2. DIFFERENT POWER GENERATION TECHNOLOGIES

50% of the installed capacity consists of fossil fuel plants, 15% nuclear, 15% renewable and 20% hydro (including pump storage). As long as a large enough water flow is available hydro plants can adapt their output very flexible and very fast. The fossil power plants are to a large extent gas fired and this portion is growing steadily: combined heat and power and combined cycles gas-turbine driven plants (gas- and steam turbines). Gas turbine driven generators can ramp up and down fast: they can be started up within 10 minutes and shut down within minutes. Steam turbine driven generators are much slower in their response, as time constants in the thermal process are relatively large. A coal fired plant needs a couple of days from completely cold to an output, at which it is possible to ramp up at a rate of 1%/min. It takes, for instance, a quarter of an hour to put into full operation an additional coal-pulverizer. Minimum output is about 25%, which is also determined by the chemical plant necessary to clean the exhaust gases. Nuclear plants show even less flexibility.

Coal-fired plants and nuclear plants are base load power generators, the output of which is adapted as scarcely as possible. Steam-turbine driven power plants with gas fired boilers are more flexible, but generally still slow in comparison to gas turbines.

Single cycle gas turbines are able to start up fast (within 10 min) and ramp up and down fast (within minutes). The number of start-stops though is generally limited and the efficiency is low (35% to maximum 40%), leading to more CO2 emission. As many gas turbines are used in combination with heat recovery (district heating, heat for greenhouses, heat/steam for industrial processes), the flexibility may be limited or special measures have to be taken to uncouple to a certain extent electricity and heat production. See also the attachment.

Combined cycle gas turbines (i.e. a gas turbine the exhaust gases of which are used to generate steam for an additional steam turbine) show a higher overall efficiency (around 60%). New technology combined cycle plants are available with a high efficiency, a high flexibility (warm start-up time within 30 minutes) and capable to handle many start-stop cycles. They can be ramped up (gas- and steam-turbine) at a rate of 10%/min [4][5].

So, hydro-plants are best suited to compensate the variable and rather unpredictable output of wind driven power plants. A drawback is that many hydro-plants installed at the European continent are either run-of-river plants with limited or none output in the dry seasons or pump-storage plants with a limited amount of stored water. An

Figure 2 Pump-storage plant Goldisthal, Germany, 1060 MW, 8 hrs

additional drawback of pump-storage is the efficiency of recovered electric energy that gives a loss of 20 to 25% [6][7]. The best applications of hydro-energy are those plants where continuously water is available and power can be produced, but at a fast controllable rate. Such plants exist in the Alpine countries and in the Nordic countries, especially Norway.

The networks of Norway, Sweden, Finland and East-Denmark are mutually synchronised, but not with the continental European region. By means of a couple of direct current interconnections a certain amount of power can be exchanged between the RG Nordic and the RG Continental Europe. The HVDC (high voltage direct current) interconnections consist of undersea bi-pole cables with rectifiers and high voltage power transformers at the AC-sides. The interconnections offer the possibility to make use of the hydro-power potential of the Nordic countries. The Western part of Denmark, with a wind energy capacity of 22% of the peak load (2010), is AC-connected to the continental European synchronous area, figure 1.

3. BALANCING POWER AND LOAD

In a synchronous region a deficit of electric power gives a decrease of the power frequency (nominal frequency 50 or 60 Hz). The inertial energy of all synchronously rotating turbines and generators makes it possible to overcome the first seconds without large power frequency deviations (a deviation of tens of mHz is already large, and larger deviations lead automatically to load shedding and/or to splitting the network). Also, immediately, the governors of all steam-, gas-, and water-turbines will increase the flow so that within seconds the deficit is compensated and the power frequency returns to its set-point. This reaction is known as the primary control. The amount of energy to compensate for the deficit (up to some per cent) is coming respectively from the steam already available in the boiler, from an immediate increase of the gas turbine inlet temperature or from a larger water flow. The power units are designed and operated to put this additional capacity available for some minutes to tens of minutes. [20]

Power generation without inertia (for instance: PV, fuel cells) or with de-coupled inertial energy (generators behind power electronic converters and doubl y fed induction generators, as applied to modern wind mills) will neither directly support the stabilizing inertial energy in the synchronous area nor participate in the primary control. However, modern control technologies make it possible that such wind mills act immediately to power frequency deviations and make shortly use of the large inertial energy stored in the rotor-blades. In other words: by the power electronic devices the inertial energy of these wind mill rotors is virtually synchronised. Though, to participate in the primary control that lasts for minutes will require an operation point with a continuous loss of wind energy in order to get margin to increase the output from the wind turbines. As such a loss has to be avoided, wind driven generators do not participate in primary control, apart from a few exceptions.

After the primary control, the secondary control takes over and brings back the output of each country or area to the original set-point, while the country or area where the deficit originated takes measures to compensate for it by new set-points or buying additional power. The original appointments, new appointments and appointments due to trading are settled within the electric energy trading markets. Within a market several electric energy and electric power packages are traded: day ahead offers for energy, spot market prices for energy balancing, primary control power prices, secondary control power prices and secondary control energy prices, along with other ancillary services.

There is a trend towards larger energy trading markets, both for gas and for electricity, with the accompanying benefits as promoted by the European Commission. Its target is to couple in 2014 the wholesale electricity markets for capacity allocation and congestion management of all members states in order to enable an efficient European wide price formation mechanism together with an optimized use of the transmission grid [8]. At the pan-European market the large local fluctuations of power generated by wind turbines will partly be cancelled out and optimal use may be made of the hydro-electric facilities across Europe, as by HVDC-interconnections the Nordic countries will be involved as well.

4. CONGESTION AND ITS MITIGATIONS

Unfortunately, there are technical bottlenecks for an optimal market mechanism as a number of transmission corridors have limited capacity[1], especially between the areas with large facilities to generate power by wind and the areas with hydro-power. The technical limits of power exchange force the areas with large power fluctuations to look for additional means to compensate for the fluctuations. In [9] estimates for power ramps due to fluctuating wind power and solar power are given. Maximum values rise from 120 MW/min in 2010 to 205 MW/min in 2020 and 470 MW/min in 2050. Essentially means to cope with such fluctuations are energy storage, curtailment of electricity generated by wind farms (in case of an excess of power), curtailment of load (demand side management, in case of a shortage of power) and highly flexible power generation. Because curtailment of wind power means also a loss of renewable energy, preference is given to storage, highly flexible power generation and demand side management. These solutions will be compared, to start with flexible generation.

[1] The European Climate Foundations points at the need to double the capacity of the electric transmission grid by 2030 in order to facilitate a 50% share of renewable power sources. And even then a considerable share of highly flexible power plants will be required. [19]

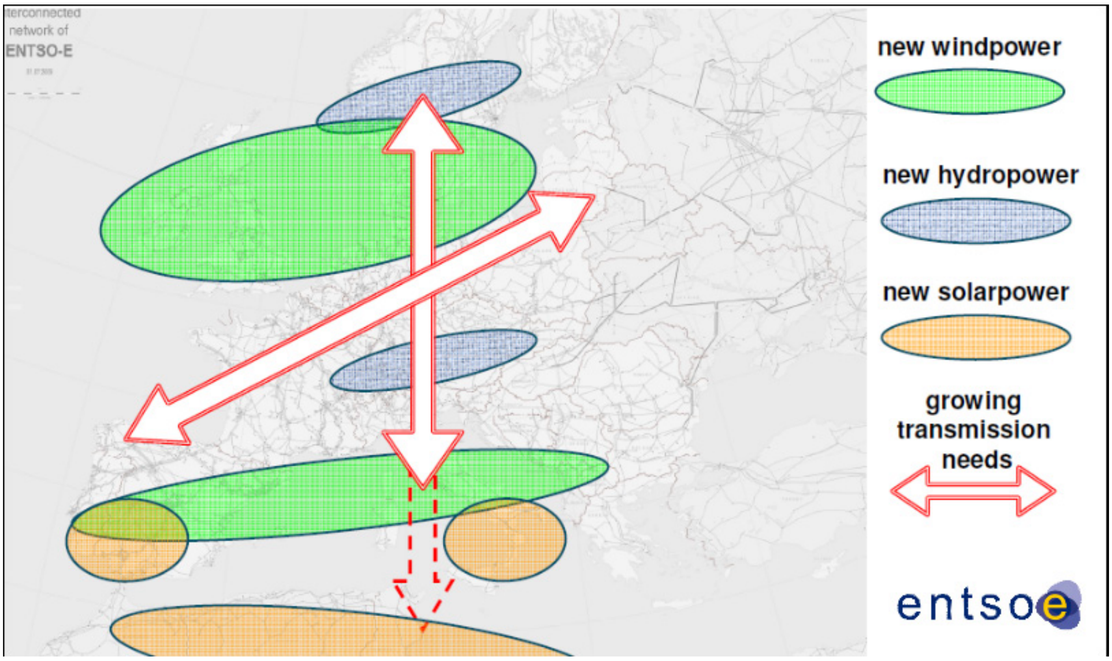

Figure3 Congestion in transmission corridors in Europe [9]

Here gas turbine driven generators play an important role, because of their flexibility in operation, but also because the ease to handle them and the relatively clean fuel they use. They don't need much infrastructure and can be installed close to sites, where the heat recovered from the exhaust gases can be used: district heating, industrial processes. Moreover by adding a heat recovery steam generator (exhaust gas heat exchanger) and a steam turbine the efficiency of the power plant can reach values as high as 61 % [5][6][18] . Reduced CO_2 emission is an important achievement and the comparison with coal fired plants can be built up as follows.
1 GWh thermal energy based on coal gives 0.36 GWh electric energy at the exhaust of 300 tonnes CO_2, while 1 GWh thermal energy based on natural gas gives 0.6 GWh electric energy (combined cycle: 60% instead of 36%) at the exhaust of 220 tonnes CO_2 [10]; the reduction of CO_2 is 56%. It should be noted that no biofuels are considered in this comparison.

In combination with district heating (combined heat and power), the energetic efficiency becomes rather large, say 90%. This applies also to gas motors, which are for instance applied to supply electricity, heat and CO_2 gas to greenhouses (see attachment). Gas motor generator sets are claimed to show a relatively high electric efficiency (49%, Jenbacher J920, 10 MWe), in combination with a large operational flexibility, as facilities to store heat are available to most greenhouse farmers (fig. 11).

5. STORAGE OF ELECTRICITY

Storage of energy and demand side management are closely related, although their roles on the market are different. Electric and magnetic energy is not stored in large quantities (electric fields in capacitors or magnetic fields in coils), so that one usually refers to another physical quantity to store electric energy: chemical energy, potential energy, inertial energy (batteries, pump-storage, flywheel). Converting electric energy into another quantity and backwards gives a loss of energy. Other important characteristics are the power and energy that can be achieved by a certain energy storage technology, the capital and operational costs, the endurable number of cycles to charge and discharge, operational and environmental consequences. In figure 4 the ratings in terms of power and energy (discharge time) are given for installed systems.

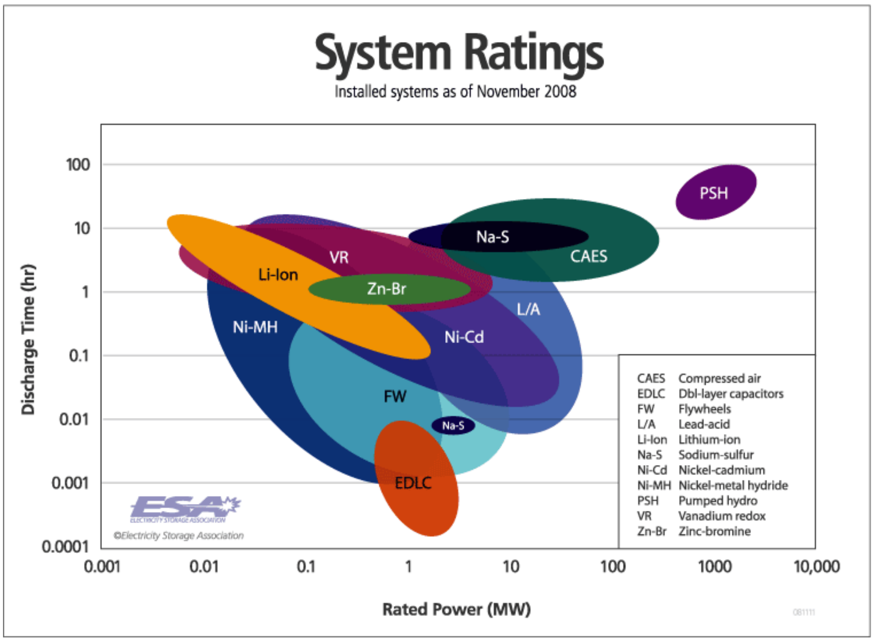

Figure 4, courtesy Electricity Storage Association [11]

Instead of storing energy during the stage of electricity transmission and distribution, one could look into possibilities to store the energy before converting it into electricity (hydro-power plants with dams) or after the conversion of the electricity to its demand side function. For instant electric energy used for cooling can be stored as ice or as another cold substance; electricity used for heating can be stored directly as heat; and electricity for electric vehicles can be stored as chemical energy in the batteries of the cars. Both this way of storage and the large time constants involved in some appliances offer the possibility to adapt the electric load to the electricity supply. Through financial impulses demand side management takes place. Load management, although summing up to 10 GW or more, still remains a small percentage of the Continental European system load [12].

Pump storage power plants in the European continental synchronous area sum up to 50 GW, forming a substantial part of all hydro plants [7][12]. They are by far the largest energy storage facility and show excellent performance characteristics, as shown in the next figures. The capital costs per kWh output and per cycle are ten times lower than those for competing technologies like CAES (compressed air energy storage), super-capacitors and flywheels and hundred times lower than various battery systems. Note that the scales of figure 5 are logarithmic.

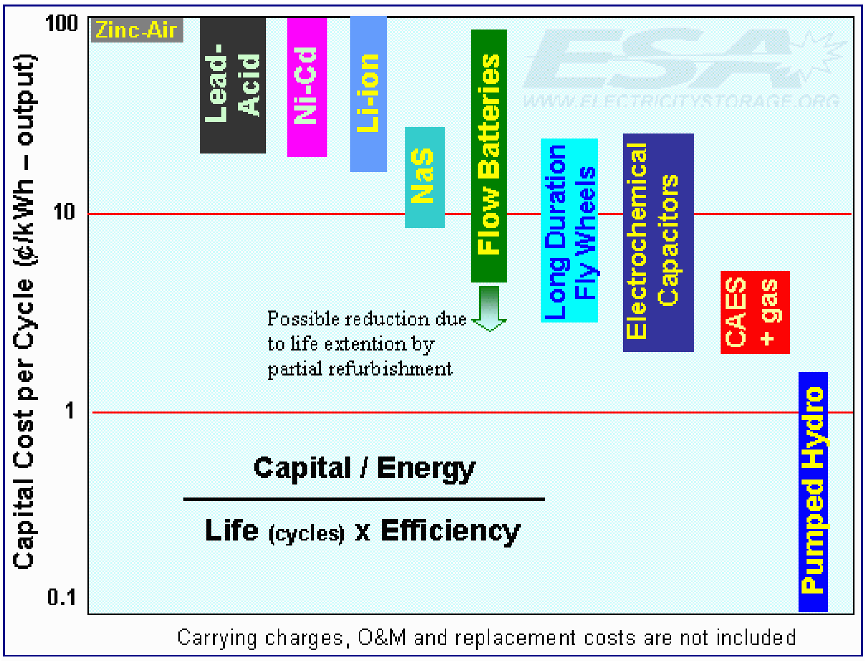

Figure 5, courtesy Electricity Storage Association [11]

6. STORAGE VERSUS FLEXIBLE POWER GENERATION

Also from the point of power and capacity, pump storage is favourite for large scale electricity systems. Being, so far, the best solution for peak shaving purposes, it has to be compared with gas turbine technology. The costs of new pump storage units are mainly depending on the hydro-technical infrastructure, which is very site depending. A rough price indication is 1000 to 2000 €/kW, while a combined cycle gas turbine will cost about 800 €/kW, almost independent on site conditions. The energy efficiency of the pump storage plant is higher, typically 80% per cycle, than that of the combined cycle gas turbine plant, typically 60%, but the electricity to pump up the water still has to be generated. Another remark is that sites for gas turbines are not so difficult to find, but sites for pump storage are becoming very scarce. Environmental and hydrological issues play an important role in the selection of sites for the water basins. Opposite, natural gas has the image of being a clean (fossil) fuel and, especially in combination with heat generation, it is appreciated as an environmentally less detrimental fuel.

From the point of view of exergy it is better to use gas for heating than electricity (unless there is a surplus of electricity), but it is even better to use gas to generate electricity and use the exhaust heat for warming houses, offices, shops, greenhouses, and so on. The optimal use of energy is the combination of co-generation (combined heat and power: CHP) with heat storage facilities, possibly at different temperatures, and heat pumps to exchange heating and cooling energy at the proper moments. These are very customized systems and therefore small scale, however highly efficient with a minimum of CO_2 emission; simplified illustrated in figure 6, a typical case in the Netherlands. The example is at the level of hundreds of houses, but also heat storage for individual houses and micro combined heat and power generators for a single house have been developed.

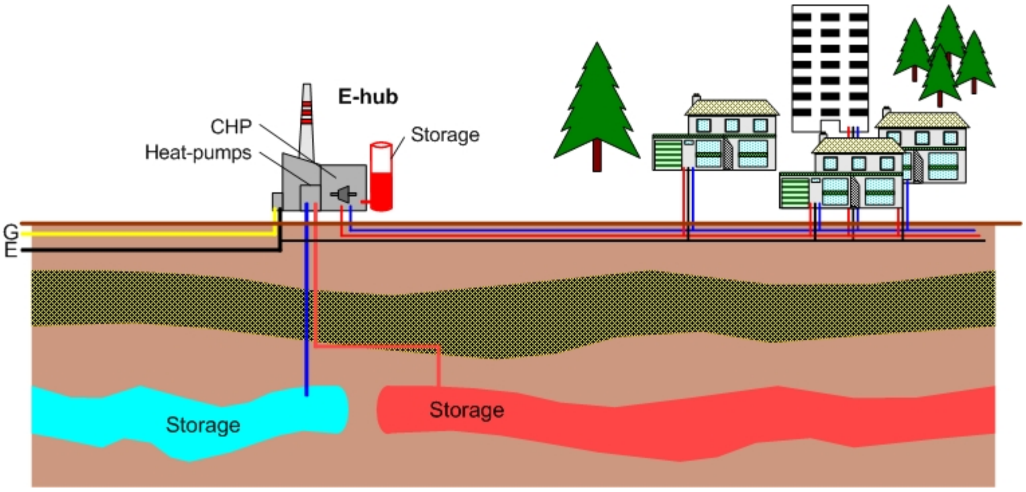

Figure 6, example of customized district heating, heat storage and heat pumps

Two examples of customized district heating and cooling in Japan have been presented in [13] and [14], including combined heat and power generation, heat storage, heat pumps, but also steam distribution and steam absorption chilling. Similar considerations as in the Dutch example play a role. By heat storage, the required flexibility of the gas motor or gas turbine driven electricity production can be achieved.

It should be noted that designing a district heating system, with or without additional heat storage facilities, is playing with the exergy efficiency for all circumstances. Among the alternative solutions to cover high heat demand, also additional gas distribution has to be considered. Usually district heating is not combined with gas supply to each dwelling. However, when high temperature heat in appliances for cooking, washing, etc. is produced by electricity, it is worthwhile also to consider the possibility to provide natural gas to each household. The additional costs for the gas distribution infrastructure with a rather low consumption per connection has been calculated and showed to be quite acceptable, at least for a situation in the Netherlands. For a project as shown in figure 6, such a gas distribution infrastructure is economically feasible when 50% to 70% of the households are connected to the gas grid (voluntarily). It is expected that most households prefer a gas supply, mainly because the Dutch are used to the flexibility and comfort of heating by gas.

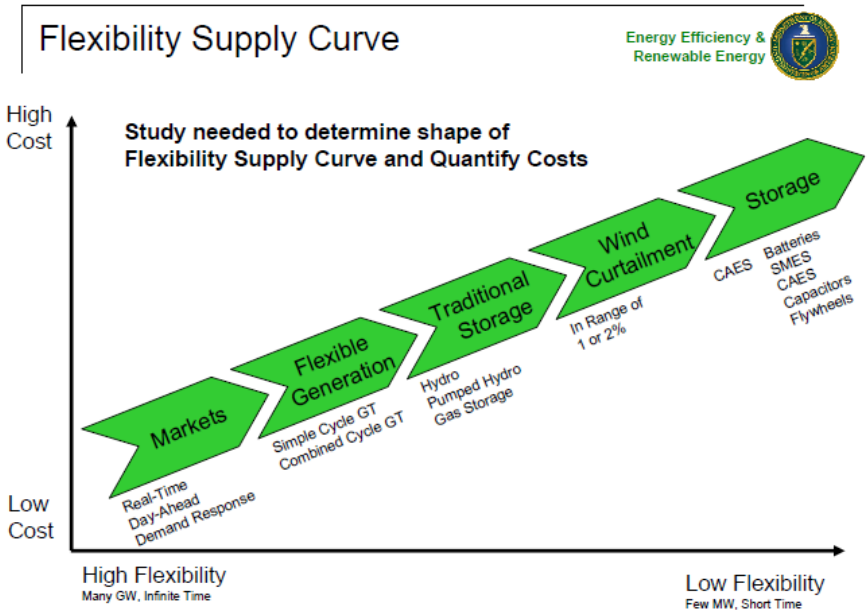

Figure 7, courtesy to Bradley M. Nickel, DoE, USA[15]

7. GASIFICATION

So far, flexible power generation, pump storage, alternative technologies to store electricity, demand side management, curtailment of wind and hydro power and heat storage have been addressed. Fore-mentioned technologies are illustrated in figure 7, where the best feasible solutions are at the left hand side: market mechanism with ancillary services and demand side management, followed by simple and combined cycle gas turbines. To the right the less feasible or preferable measures are mentioned: electricity storage technologies and wind curtailment. Because of costs and a shortage of sites hydro power and pump storage are put in the middle.

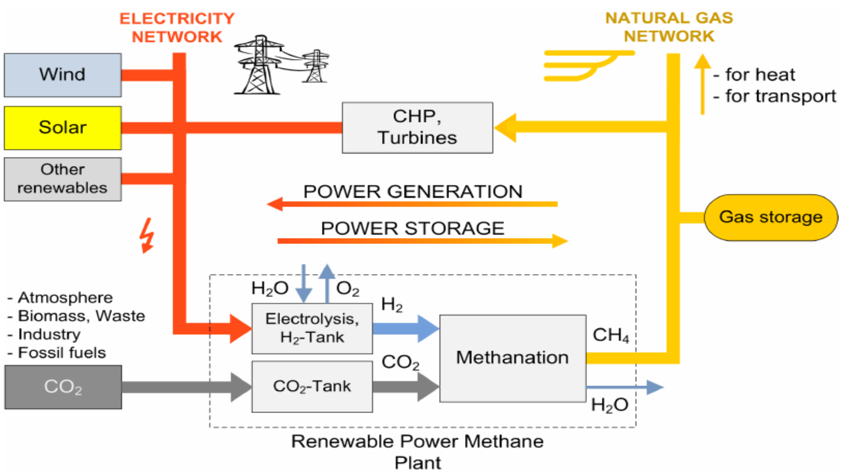

Figure8 , Electricity storage by gasification and gas storage [16]

Interesting is that in the middle also gas storage is put forward as a way to store electricity. The author addresses synthetic gas, being either upgraded biogas and gas extracted from biomass or hydrogen produced by electrolysis, based on electricity from sustainable power sources. Today, synthetic gas can be produced with an efficiency of 60 to 65% (CH_4)[1] . It is questionable whether synthetic gas should be used for electrification or for other purposes, like fuel for cars. Figure 8 shows several energy conversion cycles around synthetic gas, and figure 9 gives the features of gas storage in relation to alternative energy storage systems. Notwithstanding that all, it still is a major technical challenge to improve the conversion efficiency from electricity to synthetic gas (power to gas), thus avoiding a waste of energy. But, when technological and institutional progress has been made, synthetic gas offers an attractive alternative for energy storage and transmission.

[1] 70 to 80% (H_2)

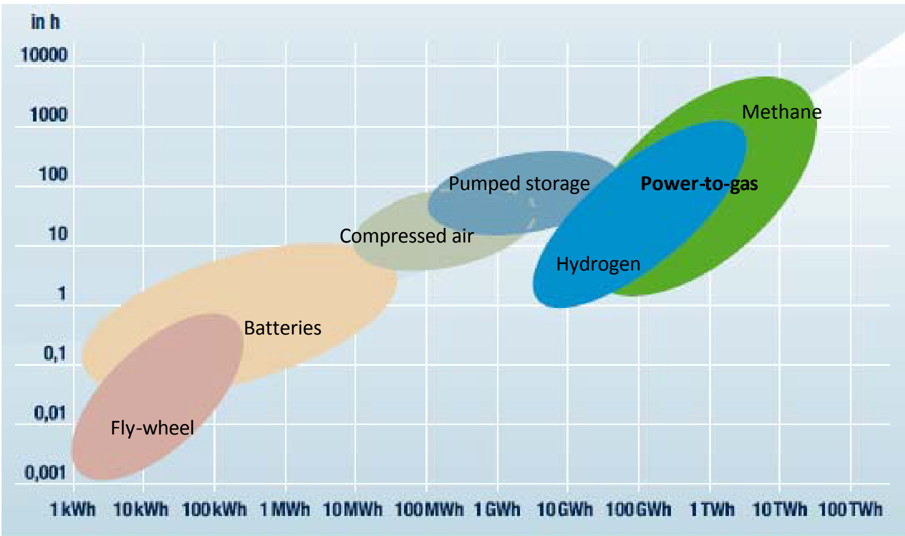

Figure 9, Comparison of Storage Techniques with typical Storage Capacity and Discharge Time [17]

8. CONCLUSIONS

- Renewable electric power sources are, to a large extent, variable and not controllable. Through the electric transmission system, other power sources have to compensate for the large fluctuations in electricity production. Despite the levelling effect by the expansion of the European transmission system, in order to facilitate the growth to 50% or even 60% renewable electricity generation in 2030 [19], a large percentage of back-up power generation facilities would still be required. The need for highly flexible and highly efficient power plants will become more acute when congestion problems in the electric transmission system are not solved.
- Highly flexible back-up power nowadays can be delivered by hydro power plants, pump storage plants and gas turbine power plants. Whereas hydro plants and pump storage facilities face site restrictions, single cycle or combined cycle gas turbine plants can be positioned relatively easily and cost-effectively at optimal locations.
- Combined heat and power generation, in combination with heat storage and heat pumps, offers good opportunities to reduce the need for primary energy and CO2 emission in residential, urban, industrial and green house environments.
- In addition, a wider implementation of demand side management (including small scale storage and/or curtailment of renewable generation) is a means to cope with the fluctuations of power generated by wind farms and other renewable sources, as solar energy systems. For large electricity storage applications, supplementary to pump storage, gasification may become a technology, that is competitive to e.g. battery storage systems.
- Gas plays a key function in the energy transition, complementary to the particularities of electric energy, especially when produced by volatile wind and solar energy conversion systems. From a macro-perspective, the production, transmission, storage and application of electricity, gas and heat should be optimized across the whole energy chain and across borders. Eventually, power to (synthetic) gas conversion may become a key technology in future power systems, combining the robustness of the gas transmission system with its capability to store energy.

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ATTACHMENT [18]

Cogeneration or combined heat and power (CHP) plants are relatively simple for the lower power range (some MW up to roughly 10 MW). They use either reciprocating machines (gas-motors, diesel-engines), small steam turbines (incineration of refuse, of biomass, of bio-gas) or small gas turbines. The heat from the exhaust gases is partly recovered and used for industrial purposes, district heating or green-houses. In green-houses also the CO2 is exploited to stimulate the growth of the crops.

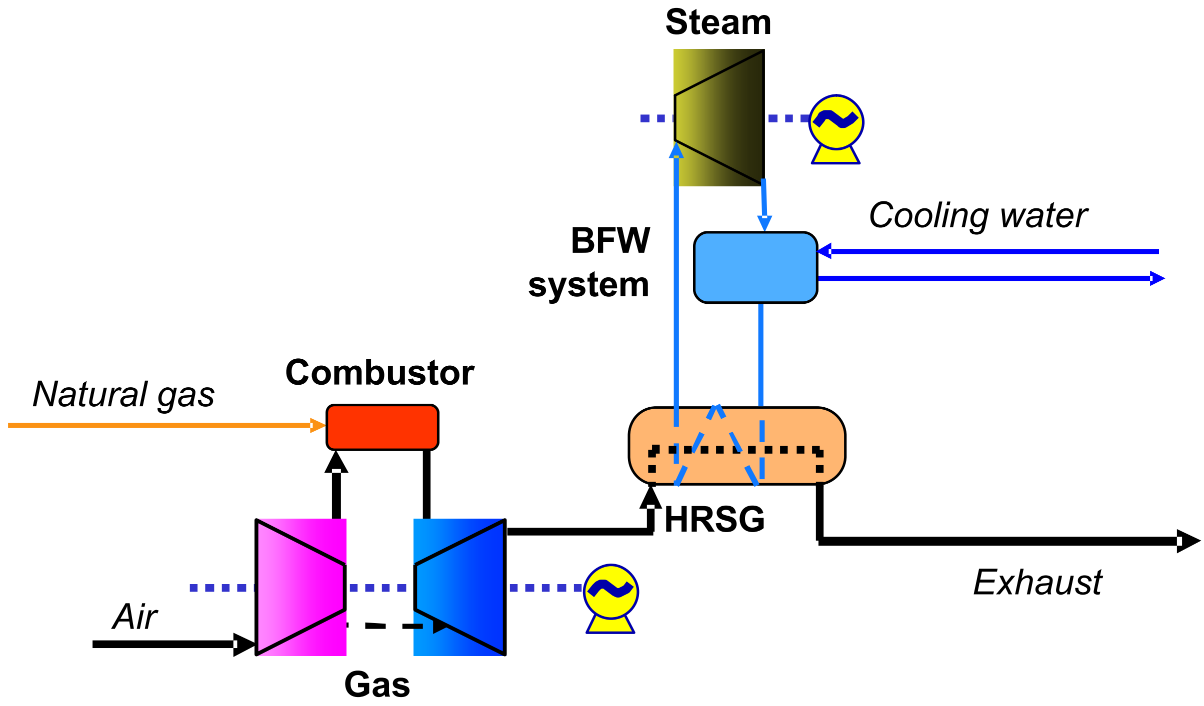

Figure 10, Combined cycle power plant

More complicated are CHP-units of several tens of MW or even hundreds of MW. They are based on either fuel fired boilers delivering steam to steam turbines and steam/heat to industrial processes, or they are based on combined cycle power plants (CCPP) with one or more gas turbines, the exhaust gases of which are used to generate steam for a steam turbine (heat recovery steam generator) and the exhaust heat (steam, cooling water, exhaust gases) for industrial processes or district heating. All rotating equipment of a combined cycle plant may be installed on one axis (air compressor, gas turbine, steam turbine and generator) or on separate axis with separate generators. When assembled on one axis, the steam turbine often can be decoupled by a special clutch, in order to facilitate start up procedures and independent operation of the gas turbine. Not only the control is depending on the number of axis applied in the CCPP, but also the dynamic behaviour of the plant, as the gas turbine/generator sets will react different from the steam turbine/generator sets or the sets with only one axis.

Heavy duty gas turbines consist of a single axis with a large compressor, combustors and a gas turbine, that delivers mechanical energy to the compressor as well as to the load (i.e. the generator). The inertia is determined by compressor, gas turbine and generator. The operational speed is relatively low for a gas turbine, as the generator runs 3000/3600 rpm or even 1500/1800 rpm. Below roughly 40% of the rated speed, the gas turbine is not capable to deliver enough torque for the compressor and therefore normally the generator is used as motor to bring the set up to speed.

Aero-derivatives are gas turbines based on the technology used for air craft gas turbines. Where in aircrafts the power of the gas turbine is used to drive the air prop, aero-derivatives use the supplementary energy to drive a generator. The size is up to several tens of MW and they normally use two axis, one to drive the compressor and the other to drive the generator. The compressor and its part of the gas turbine can run at an optimal speed, independent from the power frequency. The generator with its part of the gas turbine (called the power wheel) run at 3000/3600 rpm, but with a very low inertia.

The exhaust gases of the gas turbines are used for a steam generator in order to improve the overall efficiency, that can go up to almost 60% to generate electricity (Brayton cycle plus Rankin cycle) and to far higher percentages of the energy efficiency, when the remaining exhaust heat can be exploited usefully. To reduce the NOx-emission a small amount of water (steam) is injected in the combustor chambers, among other measures. A special design of rather small gas turbines is the STIG (steam injected gas turbine), where the steam turbine is replaced by the injection of relative large quantities of steam directly into the gas turbine (that acts as a combined gas and steam turbine). This combined function of the gas turbine is known as the Cheng-cycle.

By means of a heat recovery steam generator equipped with a gas burner (a boiler) it is possible to produce additional steam, so that the gas turbine can be operated independent from the industrial processes or district heating. Otherwise, cooling facilities may be extended to produce more electricity than corresponding to the heat demand. Heat storage is another measure to increase operational flexibility of CHP-plants (figure 11).

Figure 11, Greenhouses with CHP, supplying electricity, heat and CO_2.
Heat storage in white tanks on right hand side.