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Comparing energy storage options for renewable energy integration

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Abstract

Increasing penetrations of fluctuating energy sources for electricity generation, heating, cooling and transportation increase the need for flexibility of the energy system to accommodate the fluctuations of these energy sources. Controlling production, controlling demand and utilizing storage options are the three general categories of measures that may be applied for ensuring balance between production and demand, however with fluctuating energy sources, options are limited, and flexible demand has also demonstrated limited perspective. This paper takes its point of departure in an all-inclusive 100% renewable energy scenario developed for the Danish city Aalborg based on wind power, bio-resources and low-temperature geothermal heat. The paper investigates the system impact of different types of energy storage systems including district heating storage, biogas storage and electricity storage. The system is modelled in the hourly energy systems analyses model energyPRO with a view to investigating how the different storages marginally affect the amount of wind power that may be integration applying the different storage options. Results show the largest potential but also most costly potential for actual electricity storages.

Keywords

Energy systems analyses, renewable energy integration, energy storages

Introduction and scope

Climate change mitigation, increasing needs for energy and uncertain costs associated with future fossil energy supply are all driving factors behind an increasing utilisation of locally available renewable energy sources. Switching to renewable energy supply however, introduces certain issues in load balancing due to the fact that many renewable energy sources are not obtained in a storable way as opposed to conventional fossil or fissile fuels. In contrast, many renewable energy sources are of a fluctuating nature where energy conversion technologies tap into a use-it-or-lose-it fluctuating flow. This applies to e.g. wind power, wave power, and solar energy and to a lesser extent to run-of-river hydro power. Other sources are more constant in nature while still of a use-it-or-lose-it character such as geothermal energy. Only few renewable energy sources however are storable most notably hydro power, biomass and biogas.

Electricity demands, demands for heating and cooling and demands for transportation however must be covered at all times irrespective of momentary productions on wind turbines, photo voltaic cells, solar collectors or run-of-river hydro plants. In current system with only modest penetrations fluctuating energy sources, balance is typically ensured using fossil – and thus storable – fuel.

Maintaining the momentary balance between supply and demand in energy systems with large quantities of fluctuating renewable energy sources being utilised is the centre of attention of much research. Flexible demand, improved control of generating technologies, improved forecasting, better control strategies, inclusion of technologies such as heat pumps adding flexibility to the system, smart charging electric vehicles and storage technologies are among the paths being researched. Analyses show however, that unless storage technologies are applied, it is not possible maintaining the balance between production and demand

This paper investigates the effects of heating storage, biogas storage and electricity storage on the performance of the energy system based on a 100% renewable energy scenarios for the Danish city Aalborg.

The 100% RE scenario for Aalborg

The 100 % RE scenario for Aalborg is developed by a group of energy researchers in collaboration with Aalborg Municipality. Aalborg Municipality is among the largest in Denmark, ranking 6th in terms of population at 197000 inhabitants and third in terms of area with 1144 km^2.

Locally available energy resources are only biomass (including biogas and residential waste), wind power, low-temperature geothermal heat and solar energy. Of these, only the former three are applied in the scenario to any significant extent due to a low solar irradiation at Aalborg's latitude.

Due to the above-average population density, biomass (including waste) recourses in the scenario are allocated to Aalborg as a population-proportional amount of total Danish resources as described in (Østergaard et al. 2010).

Wind power in the scenario is variable, added at the end of the iteration process to ensure that annual energy used was matched by annual exploitation of energy resources.

Energy demand is reduced through extensive electricity savings and heat savings through insulation. Heat supply was furthermore converted to district heating from individual boilers and small district heating grids in surrounding villages are connected to the main district heating grid in Aalborg to enable a switch from natural gas CHP (cogeneration of heat and power) to other solutions.

The main district heating system is for a large part converted to geothermal heating extracting 58°C water and increasing the temperature using absorption heat pumps (AHP) driven by steam from a waste incineration plant.

Transport demand is reduced through improved public transportation and conventional petrol or diesel vehicles are replaced by either biogas vehicles (primary heavy vehicles) and hydrogen and electric vehicles (primary light vehicles).

Table 1 details the composition of the energy system.

Item	Size
Heat pumps - Local district heating grids	1.3 MW_e
Heat storage for district heating grids	0.1 GWh
CHP - central district heating grid	40 MW_e
Heat pumps - central district heating grid	24 MW_e
District heating boilers	310 MJ/s
Wind turbines	486 MW
Electrolytic converter	30 MW_e
Hydrogen storage	1.0 GWh
Individual heat pumps	9.0 MW_e
Individual solar collectors	6.0 GWh/year
Heat savings	44% reduction
Electricity savings – residential	50% reduction
Electricity savings – elsewhere	45% reduction
Industrial fuel savings	261 GWh/year
Geothermal wells and absorption heat pumps	Four 200 m^3/h system
District heating grid – expansion	One system
District heating grid – existing	One system
Biogas plant	One plant
Gasification plant	One plant
Waste incineration plant	14.0 MW_e
Electric vehicles	One system
Hydrogen vehicles	One system
Charging stations	One system
Rail and light-rail	Aalborg's share of Danish system

Table 1: Energy systems parameters for the 100% renewable energy scenario for Aalborg. Based on **(Østergaard et al. 2010)**.

Simulations of the energy system revealed however, that the system suffered from serious imbalances between production and demand of electricity, and in effect, the system needed to rely on import and export for continuous balance between supply and demand. It is thus relevant analysing the system with respect to different storage technologies' impacts.

Energy systems analyses using the EnergyPLAN and energyPRO models

The 100% renewable energy scenario was developed in an iterative process using the EnergyPLAN model, which is deterministic model modelling aggregated energy systems in hourly steps for a one year period based either on a technical operation strategy – maintaining the balance between supply and demand within the system – or on an economic operation strategy – having the system act optimally on an external electricity market. In the former, electricity import and export is reduced as much as possible while in the latter, the system imports electricity when the price is lower than the production price within the system and vice versa. In common for the two operation strategies is the operational priority given to production of a use-it-or-lose it nature; wind, offshore wind, photo voltaic, concentrated solar power (CSP), wave, river hydro, tidal, geothermal and solar collectors for heat production. Flexible demand, storages, heat pumps and dispatchable productions are then applied to either minimise electricity trade (technical optimisation) or to optimise electricity trade (economic optimisation).

While the EnergyPLAN model is capable of analysing the Aalborg system, electric storages and heat storages, it is not able to model biogas storages. The model cannot restrict the operation of biogas-based units to what is available in the biogas storage but rather proceeds to use natural gas from the grid in case of insufficient amounts of biogas in the storage. For the purpose of analysing the impacts of different storage technologies, the energyPRO model is hence applied. Where the EnergyPLAN model is created with aggregated systems in mind with e.g. one power plant in the model representing all actual power plants in the system, the energyPRO model is tailored towards project analyses with specific plants and more user-control of the operation of the individual plants (see e.g. (Andersen, Lund 2007)).

In the energyPRO model, one or more energy demands are specified using an aggregate annual demand combined with temporal distribution data down to and including a one-minute resolution. Demands are either heat, cooling or electricity demands.

Demands are covered by a number of energy conversion units being supplied by user-defined fuels assigned to the different sites. Conversion units are generally defined by installed capacities, efficiencies and fuels. Partial load characteristics may be defined as well as outputs that are functions of the operation of other units.

Heat storages are defined by volume, upper and lower temperature levels, and degree of utilisation. Losses of heat storages may be defined describing thickness of insulation, thermal conductivity and ambient temperature.

Electric storages are assumed being pumped hydro storage with a height difference, reservoir capacity, pumping and producing capacities as well as pumping and producing efficiencies. No storage losses may be modelled, however apart from this, many types of storages may be modelled using these same parameters.

Biogas storages are a part of the fuel supply system in which there is a temporal user-defined flow of fuel to the storage of a user-defined size. The drain from the storage is then dependent on the operation of e.g. CHP plants and boilers using the given fuel.

As for operation strategy, each conversion technology may be assigned a priority, partial load may be allowed or not and production to storage may be allowed or not. As opposed to the built in list of priorities in EnergyPLAN, one may hence choose to prefer an oil boiler over a solar collector in energyPRO, however for these analyses, the more energy efficient operation strategy of EnergyPLAN will be simulated where fuels (fossil or not) are only used as a last resort. The model is documented further in (EMD International A/S 2011).

Storage technologies to be investigated

Three different storages technologies are investigated in this paper; a thermal heat storage for district heating, a biogas storage and a vanadium redox battery (VRB) for electricity storage.

A thermal heat storage is a relatively simple technology consisting typically of an insulated tank connected to a high-temperature pipe at the top and a low-temperature pipe at the bottom. By using proper diffuser technology, the water column will be stratified with limited heat exchange between the hot upper layers of water and the colder lower levels. The storage enables CHP plants to produce district heating when electricity demand or electricity prices are high while enabling the CHP plant to reduce production when electricity demand or price are low. The CHP plant is thus given better load-following capability. Details for the thermal storage in Table 2 are based on temperatures of 80°C/35°C and an exploitation of 90% of the storage.

A biogas storage is also a relatively simple construction in the form of e.g. a large metal canister with a large piston inside ensuring proper pressure through gravity. Newer types include washed-out subterranean salt caverns, thick balloons or degassing tanks covered with flexible tarpaulins. Biogas is typically produced at a fairly constant rate due to the biological process and the feedstock being supplied to the biogas plant, so a gas storage enables the system to defer or move loads ahead. Details in Table 2 are based on a lower calorific value of 6.5 kWh/m^3.

Electricity storage technology is a wide area of technology with technologies utilising kinetic energy as in flywheels, electric fields as in capacitors, potential energy as in pumped hydro storage, chemically bound energy as in VRB or reversible fuel cells, or as compressed air in Compressed Air Energy Storage (CAES). Of the mentioned, only one does not rely on a change in energy form. All others require a change which lowers the efficiency while increasing costs as conversion technologies need to be included. A VRB may be perceived as a fuel cell with either side or the membrane connected to a tank of electrolyte. The power capacity is thus a matter of the scaling of the fuel cell while the storage capacity is a matter of scaling of the less expensive storage tanks.

	Cycle efficiency [%]	Converter [€/W]	Storage [€/MWh]	Annual O & M [€/MW]
Heat storage	100	n.a.	2447	**-**
Gas storage	100	n.a.	4308	-
VRB	70	1.39	67000	51000 €/(MW·year) + 2.6 €/MWh

Table 2: Characteristics of the three storage technologies. Date for VRB are based on (Danish Energy Authority, Energinet.dk 2010). Data for other technologies are based on communication with the consulting firm EMD International A/S

Energy systems analyses of storage technologies

There are a number of different performance indicators or optimisation criteria that may be applied to assess the performance of an energy system, both technical and economic. A series of criteria are deliberated in (Østergaard 2009). Here, focus is on the amount of wind power that may be integrated by the system.

In order to investigate which flexibility different storages give the system, it is necessary modelling the system in island mode, as wind utilisation would otherwise remain constant. The energyPRO model is able to model energy systems in island mode, which is then used.

Figure 1 shows results for the system with varying degrees of storage capacity. The electric storage is shown with a power of 100 MW to and from the storage while the other storages are only restricted by contents. Compared to Table 1, the system is modelled with 50 MW$_e$/ 180 MW$_{th}$ heat pumps.

Curves for the electricity storage are shown both for a 70% cycle efficiency and for a 100% cycle efficiency as one may claim that high losses in the storage would suggest a good wind power integration while it would only serve as an electricity drain.

Heat storages add flexibility to the system thereby allowing for a higher utilization of wind power, however wind power integration increase only slowly with increasing size of heat storage. Electricity storages enable a higher integration of wind power and while wind power integration as a function of heat storage capacity tends to saturate, electricity storages within the analysed range do not show that tendency. The marginal integration of wind power is the highest for small sizes of storages.

Biogas storages did not alter the integration of the system as the limited amount of biogas is used for a CHP plant taking over when wind power generation does not suffice.

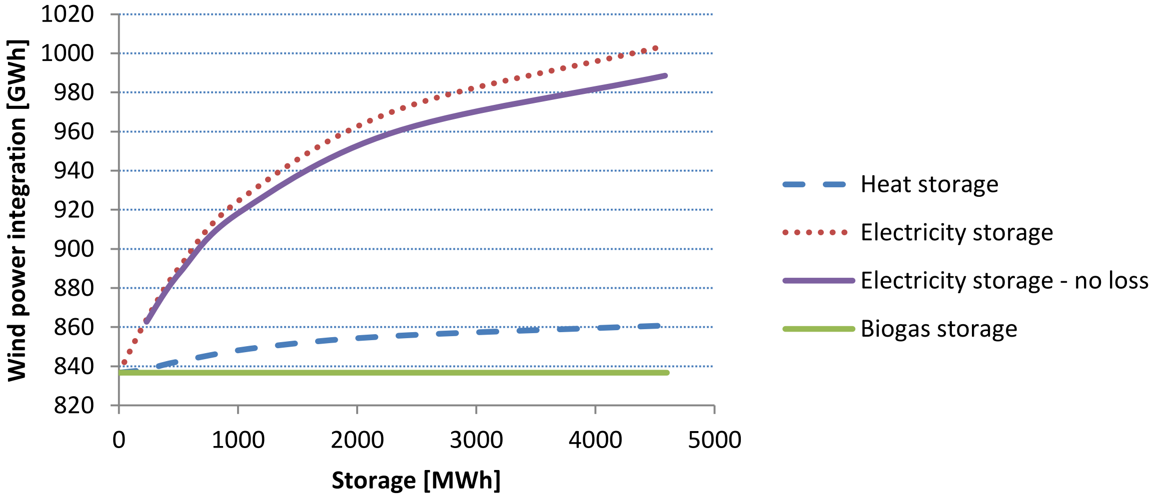

Figure 1: Wind power integration as a function of storage size. Total potential wind power production of the system is 1230 GWh

Conclusions

The analyses show that electricity storages give significant better integration of wind power than what heat storages and biogas storages can do. Space does not allow for a detailed economic appraisal, but the improved integration from electricity storages is associated with significant costs. With electricity storages being more than tenfold as expensive as heat storages, the potential for heat storage must be given preference. This applies mainly in systems in temperate climates where heat generation may be furnished by heat pumps whereby the regulating capability of these may be exploited.

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