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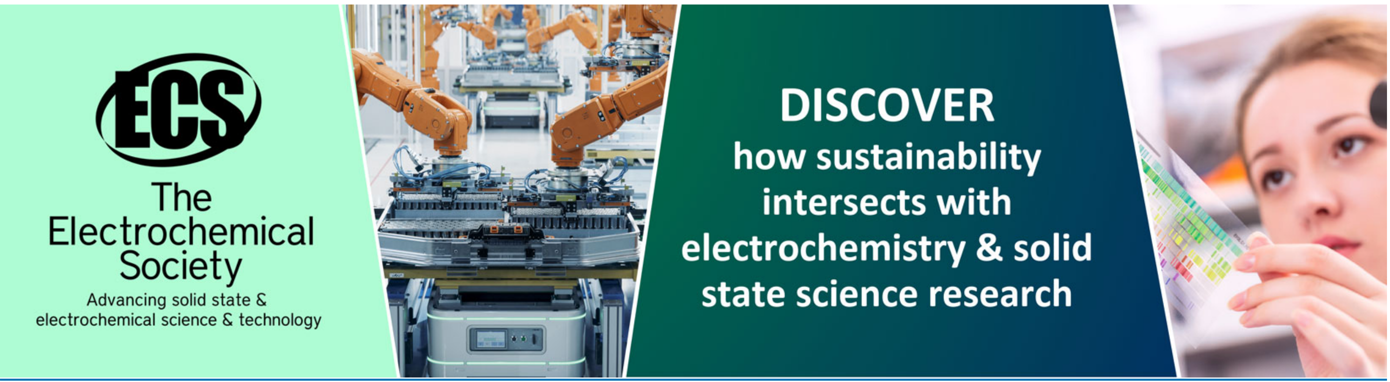

Integration of compressed air energy storage with wind generation into the electricity grid

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Abstract. Integration of renewable electricity from wind farms into the electricity grid presents challenges because wind is a highly variable resource whereby the amount of power generated depends on local wind speed, air density and wind turbine characteristics. Energy storage is one possible approach to mitigate power fluctuations and quality issues. Among presently available technologies to store energy, Compressed Air Energy Storage (CAES) shows many attractive features. This work focuses on techno-economic modelling and analysis for the integration of wind turbines with CAES into the power grid. To have a deep understanding of the performance, characteristics and benefits of system integration, technical and economic models for CAES processes are developed in the processes simulation software ECLIPSE. To conduct this study, two scenarios that are each dependent on generation scales and locations were proposed; (1) centralised CAES (based on the diabatic method) (2) distributed CAES (based on the adiabatic approach). The nominal power generation of centralised and distributed CAES systems were given as 280 MWe and 5 MWe, respectively. The impact of CAES systems on the electricity market is also discussed. Techno-economic analysis of the modelled centralised CAES system showed round-trip efficiency of around 53.6% (and around 56.7% for the modelled distributed CAES system). Specific investment was found to be around €585/kWe (€2452/kWe) and break-even electricity selling price to be around €111/MWh (€275/MWh). Their CO_2 emissions were found to be compatible with the average CO_2 emissions of UK CCGT power generation.

1. Introduction

Electricity generated from the burning of fossil fuels has many environmental problems, one of which is climate change caused by the large amount of carbon dioxide (CO_2) that is emitted during the fossil fuel combustion process. Dealing with global climate change, therefore requires to develop solutions to reduce the carbon footprint. Increasing the supply of renewable energy would help us replace carbon intensive energy sources and significantly reduce CO_2 emissions. Wind power is a low carbon energy source and its installed capacity has increased rapidly in the last ten years. To promote the development of green electricity market many governments have provided R & D funding, regulations and financial support to promote the growth of wind generation [1]. The UK became the world's largest producer of offshore wind generation in October 2008 [2,3]. As of year-end 2017, the UK's offshore wind market accounted for 36% of global installed capacity with 5.8 GW of capacity installed and commissioned. A further 4.6 GW of capacity is under construction or with a confirmed final decision, and another 3.6 GW has secured a contract for difference [4,5]. It is thus confirmed that the UK is capable of generating 10GW of offshore wind by 2020 [6,7]. The Republic of Ireland has 3.4 GW of installed onshore wind capacity from 260 wind farms. During 2016, 22.3% of electricity generation was from wind power [8].

Integrating large quantities of wind power into existing electricity grids presents a significant challenge to ensure that electricity supply constantly matches power demand. The fact is that wind energy is uncertain and variable, and therefore it is unable to be guaranteed to meet the power demand in the day. Figure 1 shows the wind power daily generation from a selected wind turbine located in Ireland [9]. Both graphs demonstrated high and frequent fluctuations. At 10-minute intervals the maximum power level changes were 317 kW (up to 37% of rated power). This increases issues inherent to the integration of a great number of wind turbines into power networks. Technically, this variability causes supply imbalance, which will increase the ramping duty and flexibility requirements for coal and gas generators. To maintain the balance between power generation and consumption many generating units are commonly scheduled for daily load cycle operations, due to system demand variations, resulting in a considerably lower capacity factor for some plants and a higher electricity price at certain times.

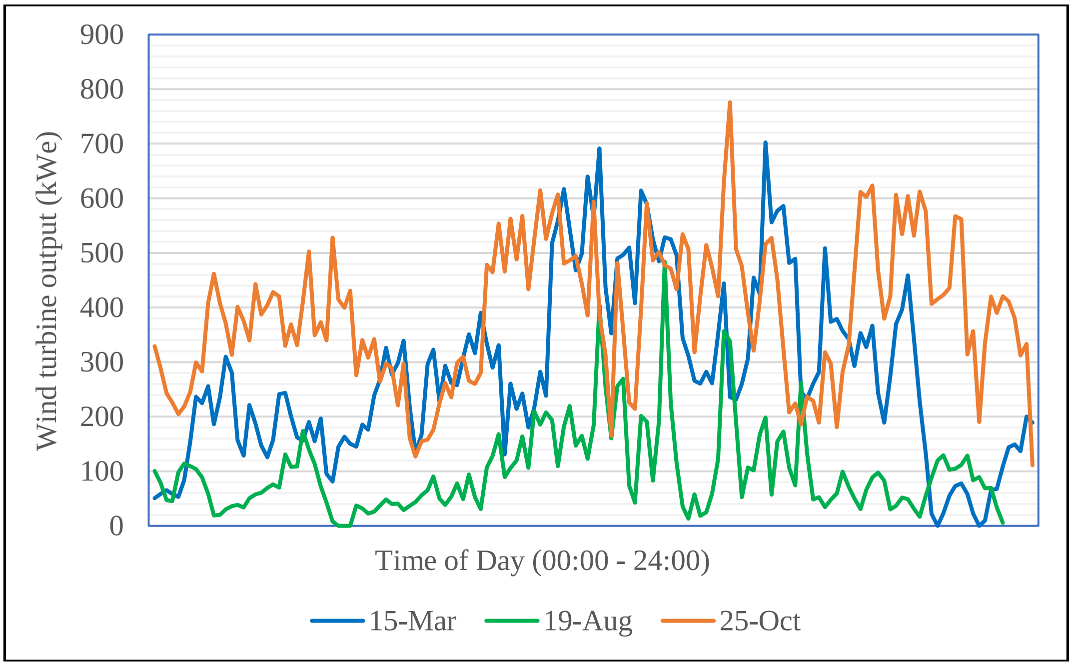

Figure 1. The daily output of a wind turbine in Ireland.

One of the most promising options, which is capable of managing the fluctuation of wind power, is Compressed Air Energy Storage (CAES). Generally speaking, CAES plants use lower cost electricity or surplus electricity generated from renewables during periods of low energy demand to compress and store ambient air in an underground cavern, or above ground in large storage vessels. When electricity is needed the compressed air is released, heated up and expanded in turbines to generate electricity, effectively providing a buffer against short term interruption of power supply. Even though the concept of CAES is more than 50 years old, there are only two operating CAES power plants in the world – a 290 MWe plant in Huntorf, Germany which was commissioned in 1978 and then upgraded to 321 MWe in 2007 [10] and another 110 MWe plant at McIntosh, Alabama in USA which was constructed in 1991. Large underground salt caverns at depths of 600 m and 450 m haven been utilised in the Huntorf and McIntosh power stations to store compressed air. A drawback of conventional CAES systems (large scale) is that they are limited by the location of the underground cavern.

The objective of this study is to carry out the techno-economic evaluation of CAES systems for use in grid integration of variable renewable energy. To provide a better understanding of the performance, characteristics and benefits of systems integration, steady-state models for the CAES processes, developed in ECLIPSE [11], are used. To conduct this study, two scenarios of different generation scales and locations, (1) Centralised CAES (grid scale) (2) Distributed CAES (small scale) are proposed. The nominal power generation capacity of the centralised CAES and distributed CAES are 280 MWe and 5 MWe, respectively.

2. Electricity market modelling

The electricity market model represents the Irish all-island Single Electricity Market (SEM) in the year 2020. The SEM is selected for many reasons: potential plans to build CAES systems in Northern Ireland, as well as high level of renewable energy, which is anticipated to reach 40% by 2020, with a majority contribution coming from wind energy. The model is composed of two regions: the SEM and the GB region. The SEM region has a detailed representation, whilst the GB region has simplified design aiming at replication of import/export power from/to the SEM region. All thermal generators are presented by unit scale, including their technical and economic behaviours and constraints, including functions of heat rate, start-up profiles, ramp rates, minimum up/down times, forced and maintenance outage profiles. Wind power profiles are included at 30 minutes time resolution. In an attempt to capture high spatial and temporal resolution of wind power, it has been produced by linear extrapolation of the 2015 regional wind profiles considering future wind energy targets and regional wind constraints [12-14]. The unit commitment and spot price settlement are optimised based on the unconstrained mandatory gross pool electricity market structure. They are defined by chronological market optimisation with a mixed integer algorithm and an objective function of total system costs minimisation.

3. Process simulation and assumptions

To perform the technical, environmental and economic evaluation of selected CAES systems the in-house personal computer-based process simulation package, ECLIPSE was used. ECLIPSE was developed by the Energy Research Centre of Ulster University for the European Commission during the mid 1980's and it is frequently updated and validated [15]. To develop the CAES models on a fairly consistent basis, a number of boundary conditions were required. The compression unit consists of electric motor driven compressors using electricity imported from the network. The compression ratio of each stage is assumed to be constant and equal. The centralised CAES has a gross capacity of 280 MWe for up to 5 hours and requires 10 hours to fully recharge. The distributed CAES is capable of delivering full power output of 5 MWe for around 4 hours. Available underground cavern volume in the centralised CAES is around 300,000 m^3. The air volume for the above ground air storage pipelines is 9000 m^3. Air temperature at the outlet of air storage is assumed to be 40°C. The cavern and pipeline operating pressure ranges from 50 to 70 bar. The mechanical efficiency of electric motors, generators and expanders is assumed to be 98%.

4. Process description

The proposed centralised CAES plant, as illustrated in figure 2, is based on a diabatic concept and is operated like an open cycle gas turbine, except that the compressors are driven by an electric motor and expanders are mounted on a separate shaft and run at different time. For an efficient compression process the heat produced at each stage of the compression train is removed by intercoolers and then dumped into the environment. The use of intercoolers between compressors helps to increase efficiencies and to reduce temperatures to the desired level. During the discharging phase this air is preheated in a recuperator to generate electricity. To boost the air temperature for the expansion process for improving the process efficiency, natural gas is introduced. The selection of this configuration (i.e. combustion takes place at the front of the gas turbine) avoids operating the first stage high pressure turbine at the high temperature [16]. Since the centralised CAES plant consumes additional fuel, it still emits CO_2, but shows relatively lower levels. Due to its high installed energy storage capacity, a centralised CAES system allows the energy storage system to be connected to the transmission network, dealing with the major operational requirements of the power system.

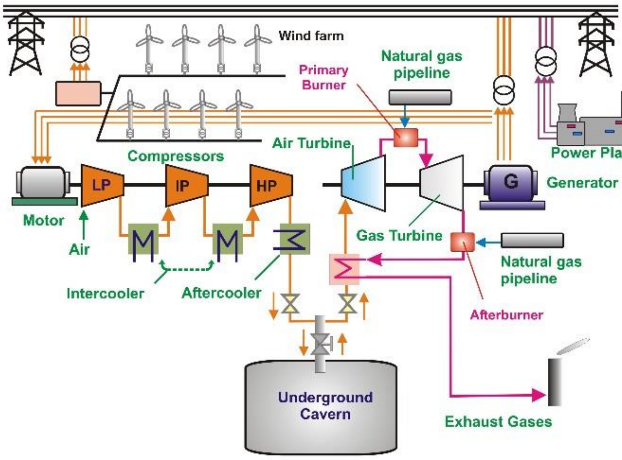

Figure 2. Simplified diagram of grid scale compressed air energy storage.

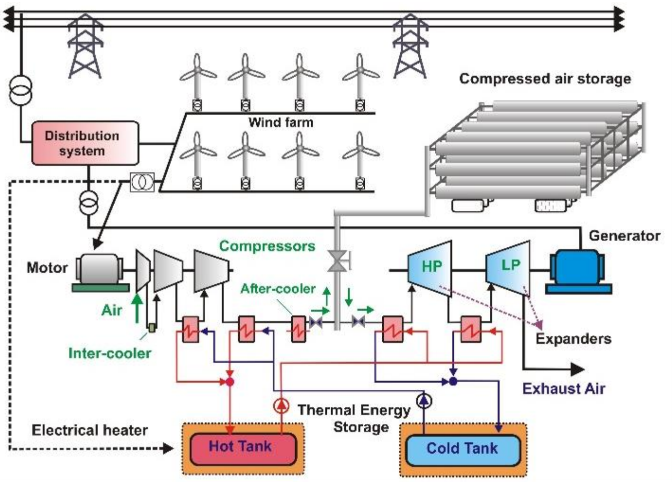

Figure 3. Simplified diagram of distributed compressed air energy storage.

The distributed CAES process, as depicted in figure 3, is based on an adiabatic concept with well insulated Thermal Energy Storage (TES), which requires no additional fuels and therefore demonstrates better efficiencies and zero emissions. Typically, a distributed CAES consists of four subsystems: motor driven compression unit, expanders and generator, the TES system and above ground air storage devices. The adiabatic process generates a large quantity of heat during the compression stage. This heat will be recovered and stored using the TES system. When the stored energy is demanded during the peak times for electricity use, the compressed air is extracted from the pipeline storage to generate power in expanders/turbines while simultaneously transferring the heat from the thermal storage to the air. With the stored thermal energy, the distributed CAES helps to eliminate any need for natural gas and hence provides a zero-carbon footprint. However, in some special situations, when there is considerable heat loss to the environment from the TES system, additional heat may be required to bring the thermal fluids up to their normal operating temperature. Due to the lower capacity value, the distributed CAES will be connected to the distribution network.

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5. Simulation results and discussion

The economic analysis was performed to determine the Breakeven Electricity Selling Price (BESP) of electricity generated in the CAES plants. All the cost of capital was adjusted to 2017 EUR. The results of the simulation are presented in tables 1 and 2.

Table 1. Process simulation results for the CAES plants.

	Centralised CAES	Distributed CAES
Air storage volumes, m^3	300,000	9000
Average compression power, MWe	107.6	3.7
Compression time, hours	10	10
Air turbine power output, MWe	280	5.0
Power generation time, hours	5	4.2
Plant occupancy, %	20.8	17.5
Thermal input, MW (LHV)	307	-
CO_2 emissions, g/kWh	496	0
Round-trip efficiency, %	53.6	56.7

Table 2. Economic results.

	Centralised CAES	Distributed CAES
CAES compressor(s)' cost, k€	21,360	1,660
CAES expander cost, k€	94,170	2,184
Heat exchanger(s)' cost, k€	4,250	702
Thermal oil/tanks cost, k€	-	1,428
Compressed air storage cost, k€	22,680	4,688
Total capital investment (incl. 10% contingency), k€	178,090	13,327
Specific capital cost, €/kWe	585	2452
Operating, maintenance and insurance cost, k€/yr	8,190	490
Compression electricity cost, k€/yr	20,480	337
Fuel cost, k€/yr	10,070	-
Capital expenditure return, k€/yr	17,770	1,278
BESP, €/MWh	111	275

With the centralised CAES system, the thermal input of natural gas was 1535 MWh and the electricity generated by the air turbines was 1400 MWh (i.e., 280 MW x 5 hr) per day. The consumption of imported electricity was 1076 MWh, resulting in a round-trip efficiency of 53.6% (LHV). With regard to environmental concerns, direct stack CO_2 emissions from natural gas combustion and indirect CO_2 emissions derived from grid electricity were estimated to be 225g CO_2/kWh and 271g CO_2/kWh (grid electricity CO_2 emission factor of 352g CO_2/kWh (2017) was assumed [17]), respectively. This resulted in the total gaseous CO_2 emissions of 496g CO_2/kWh which is comparable with the 487g CO_2/kWh figure for a CCGT [18].

For the distributed CAES system, the total electricity consumption of the compression system was 37 MWh per day. The heat exchangers between the compression stages recovered 29 MWh of thermal energy. The CAES plant generated 21 MWh of electricity during a period of 4.2 hours, leading to an efficiency of 56.7%. Without using any fossil fuels, the distributed CAES reduces its carbon emissions to zero, as required compression power is supplied by wind turbines. If the CO_2 emission rate of CCGT power generation is calculated using value of 490 g/kWh, annual CO_2 savings from the distributed CAES would be around 3,750 tonnes.

With the centralised CAES system, the capital investments of compressors, the compressed air cavern and expanders/turbines were estimated at €21.4M, €22.7M and €94.2M, respectively. The total installed capital cost of the centralised CAES was €178.1M, which was equivalent to a specific capital investment of €585/kWe. The imported electricity cost was €20.5M/yr and the operating and maintenance costs (O&M) were €7.9M/yr. The addition of natural gas increased the costs by €10.1M/yr. For the CAES plant to have a zero net present value over the project life a BESP of €111/MWh was needed.

For distributed CAES, the TES unit would cost about €1.43M. The capital costs of compressors, expanders, air storage devices were estimated at €1.66M, €2.18M and €4.69M, respectively. Its total capital cost of the CAES was €13.33M, resulting in a specific cost of €2452/kWe. When the capital expenditure returns of €1.28M/yr, imported electricity cost of €0.34M/yr and an operating and maintenance cost of €0.49M/yr were considered, a BESP of €275/MWh was estimated. This is far more than the cost of the centralised CAES plant. There are two main reasons that cause the high BESP. The first is due to the small scale CAES system. The second cause of the high BESP results from a wind turbine capacity factor.

6. The impact of energy storage on the electricity market

The impact of CAES on the Single Electricity Market was investigated for the year 2020 with an assumption of 40 % renewable energy, predominantly wind energy. The modelling result indicated that the grid scale CAES system would potentially deliver a reduction of around 70,000 tonne of CO_2 emissions per year. It was also able to reduce the spot price from €82.9/MWh to €81.2/MWh. This resulted in a reduction of 1.12 % or €39 million of the total system costs per year. The operational profile of the CAES in the SEM for one winter week is presented in figure 4.

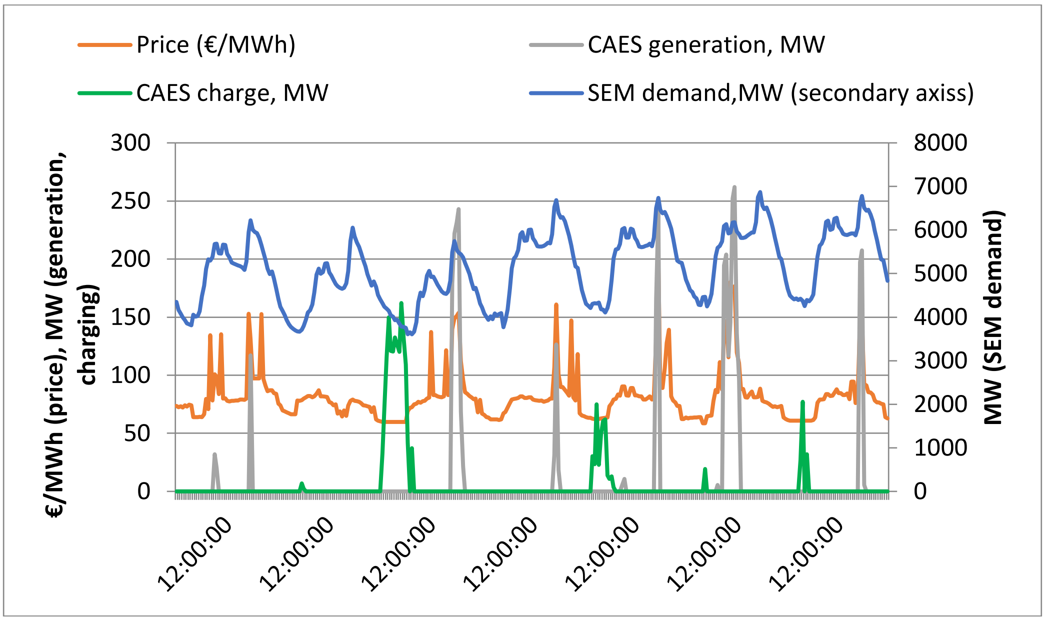

Figure 4. Operational profile for the CAES system in the SEM.

7. Conclusion

The evaluation of diabatic and adiabatic CAES systems were successfully completed using ECLIPSE software. From the above simulation results and discussion, the following conclusions were drawn:

- Both the centralised CAES and distributed CAES plants would help smooth fluctuations in wind generation.
- Simulation results showed that the diabatic CAES provided lower round-trip efficiency than the adiabatic CAES because of its considerably greater heat losses in the compression process.
- Without supplementary firing, the adiabatic CAES provided environmental benefits of zero

CO_2 emissions assuming that the required electricity was also from the wind farm.

- The diabatic CAES system was still regarded as a grid level energy storage system with relatively low CO_2 emissions, while being fuelled by the fossil fuel.
- The specific investment of the distributed CAES system was significantly higher than that of the central CAES system because of its small size.
- The distributed CAES showed a considerably higher BESP than the centralised CAES; This presents a challenge in competing with electricity prices coming from other energy storage facilities in electricity markets.
- The simulation result illustrated that large scale CAES systems would potentially reduce the spot price in the SEM.

Acknowledgments
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