The Value of Electricity Storage in presence of Renewable Energy Sources in the Future of Multi-Vector Energy Systems

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Abstract

In the near future, meeting the electricity demand becomes more challenging as the share of wind generation would be increased. Gas-fired power plants as the linkage of gas and electricity networks could manage the variable nature of wind. So, these networks would be more interdependent in the future. In this paper, the value of electricity storage to address the energy balancing challenges was investigated. A coupled operation model of gas and electricity networks is used to minimize the operational cost of both networks simultaneously. A set of further case studies on the Great Britain gas and electricity networks in 2030 has been derived to evaluate the performance of electricity storage. The results of this study validate the performance of electrical storage in presence of significant amount of wind in improving the operation of gas and electricity networks.

Nomenclatures

Superscripts

em	Emission
es	Electrical load shedding
gs	Gas load shedding
gst	Gas flow of storage facility
gsu	Gas flow from supply

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in	Injection
tot	Total
ur	Unserved reserve
var	Variable
ab	Absorption
stor	Storage

Subscripts

b	Buses
g	Thermal generators
l	Generation units
p	Pump units
s	Storage
t	Time (h)
y	Terminal

Variables and Parameters

C	Cost (£)
M	Operational Cost (£M)
P	Power generation of units (MW)
Q	Volumetric gas flow rate (m^3/s)
∂LP	Rate of change of gas linepack (m^3/s)
ζ	Efficiency
E	Energy (MWh)

Introduction

The variable nature of wind could cause important operational challenges as the share of wind in Great Britain (GB) will be increased in the near future [1]. Due to zero operational cost as well as environmental friendly features of wind, so using wind in order to meet the electricity demand is given priority. In order to compensate the variability of wind other type of generation technologies, such as nuclear, Carbon and Capture Storage (CCS) equipped coal, and gas-fired power plants (gas plants) should be employed.

Gas plants are the linkage of electricity and gas networks. In the electricity network, gas plants supply electricity while, in the gas network, these plants are gas demand as they consume gas for electricity generation. Hence, wind variability is reflected as variable gas demand in the gas network.

The role of flexibility options in order to deal with energy balancing challenges of power systems in presence of Renewable Energy Sources (RES) is presented in several studies [2]-[4]. Flexibility is defined as the ability of a system in dealing with generation and demand variability given that an acceptable reliability is maintained [2]. In [3] it is illustrated that in order to supply 80% electricity from variable RES in an isolated power system such as ERCOT in Texas, USA, it is needed to enhance generation flexibility and virtually eliminating of minimum generation constraints imposed through must-run baseload generators. It is proposed to replace conventional regulation and spinning reserves with a combination of demand side response, energy storage, and use of curtailed variable generations. Danny Pudjianto *et al* studied about the value of electrical storages in terms of costs and duration work in GB electricity system. The proposed model optimizes the investment side by taking into account the security and reserves constraints. The results show the role of electrical storage in reduction of the required investment in system reinforcement as well as transmission congestion management [4]. In the mentioned research the gas supply constraints were not considered.

Few researches study the impacts of wind generation on the gas network operation in detail [5] - [6]. Therefore, in this paper, the value of electricity storage as a flexible option in order to address the balancing challenges of supply and demand in the operation of electricity network as well as gas network is studied. In order to validate the role of electricity storage, a set of case studies on the GB gas and electricity networks in 2030 is derived. The objective is to minimize the operation costs of the gas and electricity networks simultaneously.

Modelling Methodology

The updated version of the Combined Gas and Electricity Networks (CGEN) model [10] as an optimization tool for detailed analysis of operation of coupled gas and electricity networks was used. The model is able to minimize the operational costs of both networks simultaneously. The costs of power generation, gas supplies, electrical and gas load shedding, emission penalties, storage operations, and negative changes in linepack are considered in the objective function, which is shown in (1) -(3). Linepack is the amount of gas stored in the pipelines in order to deal with fast demand changes in the gas network.

$$M^{\mathrm{elec}} = \sum_t \left\{ \left(\sum_l \left(C_l^{\mathrm{fuel}} + C_l^{\mathrm{var}} \right) P_{l.t} + \sum_b C^{\mathrm{es}} P_{b.t}^{\mathrm{es}} + \sum_g \left(C_g^{\mathrm{ur}} P_{g.t}^{\mathrm{ur}} \right) + C_{g.t}^{\mathrm{su}} + C_{g.t}^{\mathrm{sd}} + C_{g.t}^{\mathrm{em}} \right) \right\} \tag{1}$$

$$M^{\mathrm{gas}} = \sum_t \left\{ \begin{pmatrix} \sum_y C_y^{\mathrm{gas}} Q_{i.t}^{\mathrm{gsu}} + \sum_s \left(C_s^{\mathrm{in}} - C_s^{\mathrm{ab}} \right) Q_{s.t}^{\mathrm{gst}} + \sum_m C^{\mathrm{gas}} \, \partial LP_{m.t} \\ + \sum_n C^{\mathrm{gsh}} \, Q_{n.t}^{\mathrm{gsh}} \end{pmatrix} \right\} \tag{2}$$

$$M^{\mathrm{tot}}(£) = \min\left(M^{\mathrm{elec}} + M^{\mathrm{gas}} \right) \tag{3}$$

In the electricity network, following constraints for each time step are taken into account: power balance between the supply and the demand, generators physical limitations, transmission lines capacity, generators characteristics such as minimum up/down time, and available spinning reserve. The electricity storage at each busbar of the electricity network and each time step is modelled as follow:

$$E_{t,b}^{\mathrm{stor}} = E_{t-1,b}^{\mathrm{stor}} + E_{t,b}^{\mathrm{ab}} * \zeta - E_{t,b}^{\mathrm{in}} \tag{4}$$

where, E^{ab}, E^{in} are limited by the rated output power capacity of the storage. Moreover, the energy capacity of the storage restricts E^{stor} . The round-trip efficacy of storage is assumed to be 70 % [4].

The gas flow through the pipelines is calculated by the Panhandle A equation introduced in [11]. Constraints of the gas network are as follows: the gas flow balance, pressure constraint, gas terminal and storage facilities limitations, and gas compressor operation limits.

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All constraints of gas and electricity network have to be met simultaneously. Constraints of gas and electricity networks operation is formulated in detail in [5], [6] and [7].

It is worth mentioning that the model was formulated using the FICO Xpress optimization tool. The Xpress-mmxnlp solver for MINLP (Mixed Integer Non-Linear Programming) was applied to minimize the objective function over the studied time.

Case Studies

GB coupled gas and electricity system operation is modelled in 2030. Performance of electricity storage with 5 Giga Watt (GW) output power capacity and 15 Giga Watt hour (GWh) energy capacity (*5 GW* case) and 10 GW/30 GWh (*10 GW* case) capacity in order to address electricity balancing challenges is evaluated and compared to the reference (*ref)* case. In the *ref* case no special flexibility is considered to mitigate the consequences of integration of large capacity of wind generation into the grid. The impact of employing electricity storage with different capacities on the operation of the gas network (i.e. compressor power) is also investigated. Table 1 presents the generation mix used in this study.

The GB gas National Transmission System (NTS) as well as 29-Busbar electricity transmission networks layout are presented in Figure 1. The electricity demand and the gas demand data are taken from [1] and [8].

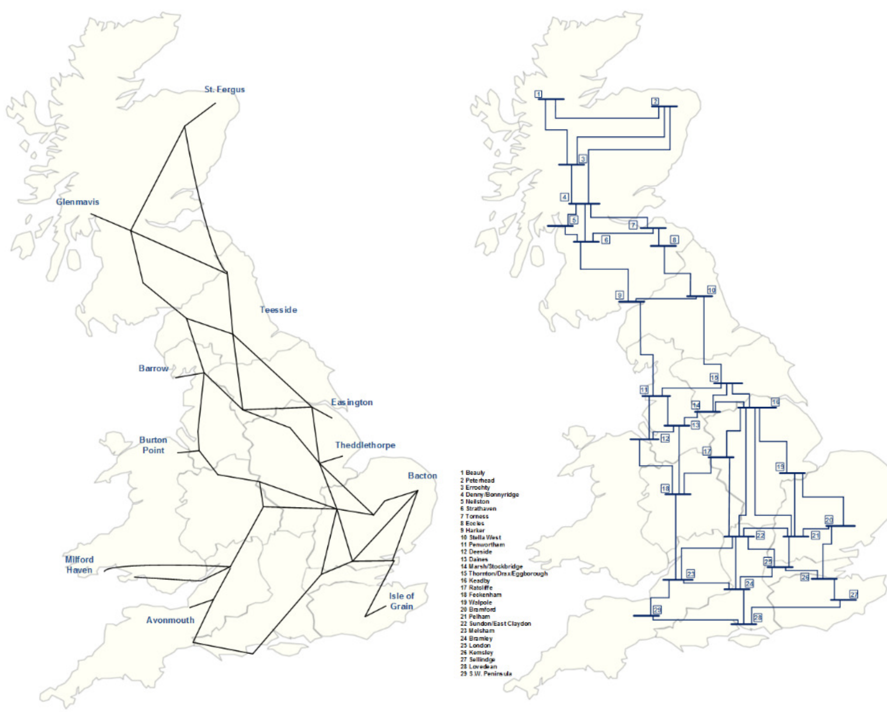

Figure 1: GB gas NTS network; GB 29-busbar electricity transmission system

Table 1: Power generation mix in 2030 [1]

Generation Technology	Capacity (GW)
Wind	52
Gas	33
Interconnector	11.5
Nuclear	9
Coal with CCS	4.5
Pumped storage	2.7
Other	2.3

Numerical Results

Unit Commitment of Thermal Generating Plants**:** As it is presented in Figure 2, number of committed gas plants are less in storage cases in comparison to the *Ref* case. The reason of that is in storage cases the need of gas generation to meet the demand has been decreased as storage is participating in energy balancing. Therefore, these plants are operating less frequently. As a comparison of *5 GW* and *10 GW* cases, in *10 GW* case as more storage is available, so less need of gas plants and therefore the number of committed gas plant units to the electricity network is reduced.

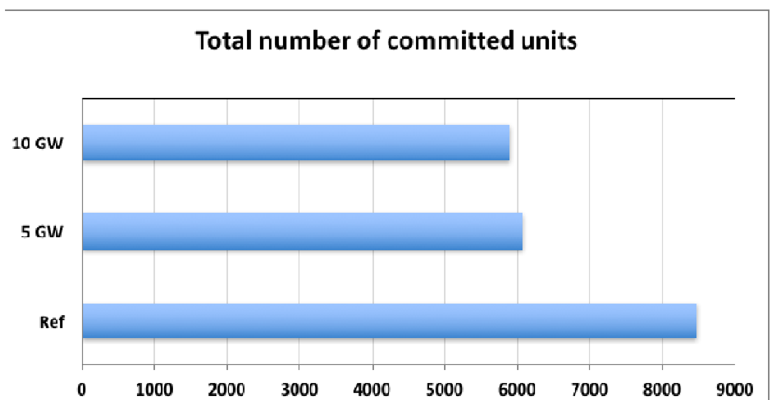

Figure 2: Total number of committed gas plant units in different cases.

Power Generation Mix**:** In Figure 3, changes in the electricity generated by different types of technologies in respect to the *Ref* case are presented. Electricity generated by nuclear changes softly in different cases. In *5 GW case*, electricity generated through gas plants over the week has reduced by over 110 GWh. This reduction is compensated mainly by increase in electricity generated by wind. In *10 GW case* because of more available storage capacity, absorption of more wind generation reduces the output from gas plants (130 GWh). In addition, importing electricity through interconnectors is almost -30 GWh less in storage cases. Through the electricity storage option, it is shown that the need of gas plants to deal with wind generation has been decreased. Consequently, less variable gas demand for electricity generation in the gas network is required.

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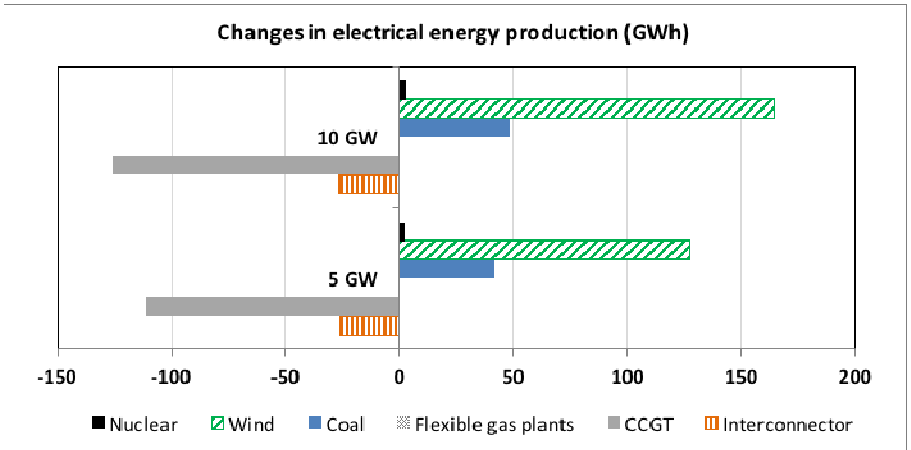

Figure 3: Changes in electricity generation from various type of technologies, compared to *Ref* case

Wind Curtailment**:** Curtailed wind over the modeling time horizon for different cases are shown in Figure 4. As it can be seen employment of electricity storage reduced the curtailed wind as part of the excess wind power is absorbed by the electricity storage. Electricity storage reduced the wind curtailment almost by 33% and 42% (level to the *Ref* case) in *5 GW* and *10 GW* cases, respectively. Nevertheless, at some periods total electricity generated through wind and must run technologies is more than demand and due to the limitation of electricity storage capacity, a proportion of wind generation is curtailed. In these cases, about 255 GWh and 210 GWh wind was curtailed especially during the high wind periods.

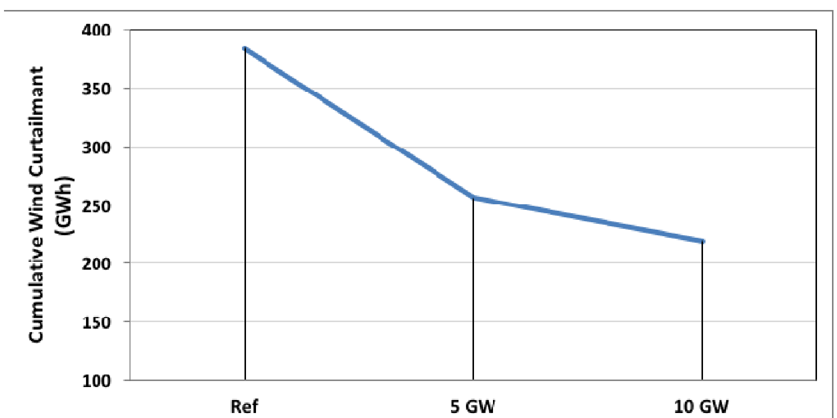

Figure 4: Wind curtailment in different case studies

Gas Compressor Operation**:** Gas pressure will be lost in the gas network due to the friction of the pipelines. So, the installation of compressors is considered [9]. The role of compressor is to maintain the gas flow pressure in an acceptable range.

Table 2: Compressor power consumption (MWh)

Case Study	Power Consumption
Ref	1538.2
5 GW	1415.7
10 GW	1386.8

The compressor consumption power in different cases are presented in Table 2. It could be concluded that in storage cases the gas pressure in the pipelines is more as the prime mover consumption power of the compressors in order to increase the pressure, is less than *Ref case*.

Operational Cost**:** The operational cost of the gas and electricity networks over the typical winter week in presence of different electricity storage capacities is shown in Table 3. The lowest operational cost was achieved through *10 GW* case due to the fact that more storage capacity is available for injecting and absorbing the required power to the network. The operational cost of electricity storage is assumed to be zero. The significant cost reduction in the electricity network is related to the fact that in the economic dispatch of power generation, storage as a cheaper option is employed more than the gas-plants and interconnectors. As a result, the gas consumption for power generation is decreased and so the gas network operational cost has been reduced as well. The considerable cost savings (£ 22.12M and £ 23.08M) over the week in electricity storage cases indicate the value of this flexible option.

Table 3: Gas and electricity networks operational costs over the week in £M

Case Study	Electricity Network	Gas Network	Total
Ref case	69.80	801.13	870.93
5 GW case	53.56	795.24	848.81
10 GW case	53.37	794.47	847.84

Conclusion

An optimization model for operation of the Great Britain (GB) coupled gas and electricity system was implemented in order to address the supply and demand balancing challenges of Renewable Energy Sources (RES) integration to the network. In detail, the performance of employing different capacities of electricity storage in presence of wind were studied. Also, the impacts of this flexibility option on operation of the GB gas network such as compressor consumption power were analyzed.

Utilizing electricity storage indicates the reduction of wind curtailment from 33% in case of 5 GW/15 GWh storage capacity to 42% in case of 10 GW/30 GWh storage capacity. Better management of the gas network operation was presented through power consumption of the gas compressors. In addition, electricity storage contributed in considerable decrease of the operational cost of the GB gas and electricity supply systems. The reason of this performance of electricity storage is due to the fast reaction of storage in storing and injecting of electricity, acceptable efficiency, and zero-operational cost feature of this device.

For the next step of this research, the investment perspectives of employing electricity storage should be taken into account.

References

[1] National Grid (2014). UK Future Energy Scenarios 2014.

[2] Ma, J., Member, S., Silva, V., Belhomme, R., Kirschen, D., and Ochoa, L., (2013) Evaluating and Planning Flexibility in Sustainable Power Systems. IEEE Transactions on Power Systems, vol. 4, no. 1, pp. 200–209.

[3] Denholm, P., Hand, M., (2011). Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy, pp. 1817-1830.

[4] Pudjianto, D., Aunedi, M., Djapic, P., Strbac, G., (2014). Whole-Systems Assessment of the Value of Energy Storage in Low-Carbon Electricity Systems, IEEE Transaction on Smart Grid, vol. 5, no. 2, pp. 1098-1109.

[5] Qadrdan, M., Chaudry, M., Wu, J,. Jenkins, N., Ekanayake, J., (2010). Impact of a large penetration of wind generation on the GB gas network, Energy Policy 38, pp. 5684-5695.

[6] Martinez-Mares, A., Fuetre-Esquivel, C., (2012). A Unified Gas and Power Flow Analysis in Natural Gas and Electricity Coupled Networks, IEEE Transaction on Power Systems, vol. 27, no. 4, pp. 2156-2166.

[7] Chaudry, M., Jenkins, N., Strbac, G., (2008). Multi-time period combined gas and electricity network optimisation, Electric Power Systems Research 78, pp. 1265-1279.

[8] UK Infrastructure Transitions Research Consortium (ITRC), (2014). National infrastructure assessment: Analysis of Options for Infrastructure provision in Great Britain.

[9] Osiadacz, A., (1987). Simulation and Analysis of Gas Networks, Gulf Publishing Company.

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