A COMPARISON OF THE POWER-TO-GAS CONCEPT AND BATTERY ELECTRIC VEHICLES TO INTEGRATE WIND ENERGY INTO ELECTRICITY NETWORKS

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ABSTRACT

The UK electricity generation sector is likely to undergo a switch from a fossil fuel based fleet towards a higher proportion of intermittent renewables and notably wind energy. This work addresses the challenges posed by a higher penetration of wind energy in the UK for DNOs: an increased need for balancing services and a bigger amount of wind electricity curtailments – i.e. wasted electricity that cannot be used. A time-based model has been developed, covering the period 2011-2030, to assess two potential schemes to cover these two issues: an industrially-sized electrolyser converting electricity into hydrogen (the so-called 'power-to-gas' concept) and an industrial fleet of battery electric vehicles with flexible charging. The methodology followed was to predict temporal distributions of wind curtailments to then assess the two schemes' capability to provide balancing services while remaining economically attractive. It was found that the levels of wind curtailments grow significantly, but become more balanced as the time goes by. The battery electric vehicles scheme shows better performances in the medium-to-long term while the power-to-gas concept is more appropriate for the short term and proves to be more flexible. This work can be used as a decision-support tool by DNOs or other parties interested in covering the issues raised by a higher proportion of intermittent renewables.

1. INTRODUCTION

The UK government has established a legally binding target to reduce the UK's greenhouse gas emissions by 80% by 2050 compared to 1990 levels. As the power sector is the largest source of UK emissions today, accounting for 27% (157 $MtCO_2$) of them in 2010, these targets can only be met with a major decarbonisation of the electrical industry [1]. Such a drastic decarbonisation can be achieved through several mechanisms: energy efficiency measures, closure of many old UK coal plants and increasing deployment of low-carbon technologies (renewables, nuclear and carbon, capture and storage). The renewable electricity generation is foreseen to reach 30% of total generation by 2020 compared to 7% in 2010 [1]. The UK will then have to cope with increasing penetrations of intermittent renewables, whose wind energy will play the biggest role.
But a higher penetration of intermittent wind energy in the UK poses several challenges for the DNOs. First the needs for balancing services – the services required to ensure a stable grid in which the electricity supply always matches the electricity demand – will significantly increase. Second a bigger amount of wind electricity will be curtailed – i.e. wasted when times of strong wind coincide with times of low demand.
A range of conventional solutions has already been extensively studied in the literature [2]: an extra capacity of flexible fossil fuel plants, interconnections with other electrical grids, energy storage solutions and demand side management. All of them present however several limitations discussed in further details in reference [3].
There exist also other 'modern' solutions to cover the issues raised by higher penetrations of renewables. This paper proposes a time-based model, covering the period 2011-2030, to assess two of them: the power-to-gas concept ('P2G') and a battery electric vehicles scheme with flexible charging patterns ('BEV').
Section 2 presents in more details the P2G concept and the BEV scheme characteristics as well as the UK market for balancing services. Section 3 exposes the modelling methodology followed for both the wind curtailments simulation and the two schemes' assessment. Section 4 explores the wind curtailment distributions results from 2011 to 2030. Section 5 analyses the two schemes' performances according to carefully selected criteria. Finally, Section 6 summarizes this paper's results with some key recommendations.

2. POWER-TO-GAS, BATTERY ELECTRIC VEHICLES AND UK BALANCING SERVICES

The power-to-gas concept (P2G)

Today the majority of the hydrogen production comes from reforming natural gas and refinery gas (48%), as a by-product from chemicals production (30%) and from coal gasification (18%) [3]. There is however a small but rapidly growing market for hydrogen production through electrolysis, as described by equation 1 below.

$$H_2 0 + electricity \rightarrow H_2 + \frac{1}{2} O_2 \qquad (1)$$

The water electrolysis method still shows much higher costs than other methods but is already being used at a small scale and/or in remote areas (4% share in 2012) [4]. More recently hydrogen production through electrolysis has gained interest as a method to cover renewables intermittent and fluctuating outputs [5] and some studies suggest that the concept could reach large-scale integration in Europe by 2020 [4]. The produced hydrogen can have multiple applications but this work focuses only on the use of electricity to convert water into hydrogen that is directly injected into the natural gas grid. The main parameters of a P2G system are the electrolyser type's choice, the operating mode and the electricity sources. For this work, the PEM (Proton Exchange Membrane technology) was preferred over the alkaline technology due to its better matching with flexible loads [operational data were extracted from ITM Power confidential reports [6]]. Second, the operating mode selected was a hybrid solution (between off-grid use and continuous use) consisting in using excess wind electricity combined with the public grid only to provide economically rewarding balancing services [3].

The produced hydrogen can be inserted into the gas grid, but there is a technical barrier: the natural gas grid has been designed for natural gas (essentially composed of methane CH_4) and hydrogen is therefore often seen as an impurity for the gas grid [7]. For this reason a legal upper limit for the hydrogen molar concentration in the gas grid is generally set by most European countries: the UK has one of the tightest limit (0.1%) compared to other countries such as France (6%), Germany (2-10%) or Holland (12%) [6]. Appliances as well as the gas pipes are designed with these limits in mind. Some studies suggest however that much higher concentrations (10%) are worth considering, even in the short term [8].

The battery electric vehicles scheme (BEV)

The other scheme assessed in this paper involves an industrial fleet of battery electric vehicles with flexible charging. BEVs can indeed be seen as flexible loads for the electrical grid as, depending on the driver requirements, the time of recharge can be chosen to a certain extent. An electric vehicle can be used according to 4 different modes: the uncontrolled mode (the driver recharges its battery when he wants to), the passive demand side management (time-dependent tariffs incite drivers to recharge in time of low demands), active demand side management (an aggregator controls the recharge time thanks to time-switch devices) and the vehicle-to-grid concept (the reverse charging from the car to the grid is possible with additional and expensive technical components)[9].

For feasibility and economic reasons, this analysis focuses on an industrial fleet of battery electric cars operating under the active smart management scheme, which has a specific industrial purpose (typically forklifts in a warehouse). These vehicles were using the energy contained within their battery during the day. But the battery recharging time could be selected and modulated during the night or during the weekend as long as at the beginning of each working day the battery of each electric vehicle was full.

The UK balancing services market

These two concepts could have a significant 'easing' effect on the balancing market regarding higher integrations of intermittent wind energy. This UK balancing market is now briefly presented.

All developed countries possess a unified grid enabling a second-to-second matching of the electricity supply with the demand. A broad range of mechanisms is being used and implemented by different actors to insure this equilibrium. The balancing market is one of crucial importance, insuring the overall system has the possibility to fluctuate its demand and/or its supply. In the UK the balancing market is regulated by the National Grid: the standard UK frequency is 50 Hz and the National Grid has a legally binding requirement to maintain this frequency between 49.5 Hz and 50.5 Hz (±1%) [10]. DNOs currently do not intervene on the balancing market. However increasing distributed electricity generation is likely to change this paradigm and may compel DNOs and TNOs to jointly work on it.

The UK balancing market is grossly divided into three main categories: the frequency response, the fast reserves and the short-term operative reserves. The distinctive characteristics between these three categories are the required speed of response, the minimum capacity and the delivery period length. The frequency response market globally refers to small but very rapid changes of output/demand (speed of response inferior to 30s). The short-term operative reserves provide additional active power from generation and/or demand and is needed when the demand is greater of that forecasted, typically used in case of a plant unavailability. The fast reserves service is the intermediary service between these two first categories: it is generally used to control frequency variations that could arise from sudden and sometimes unpredictable changes in demand or supply [10].

3. METHODOLOGY

This section describes the methodology used for the 2-step model developed. The first subsection discusses the methodology to estimate the temporal distributions of wind curtailments. The second subsection presents the model used to compare the economic and 'balancing services' performances. More details are available in reference [3].

Model 1: Wind curtailment estimations

Based on a review of the scientific literature, there is no common method to estimate the share of curtailed energy for a wind farm. The model used to estimate wind curtailment temporal distributions in different locations in Scotland is presented here in six distinctive steps.

Step 1: hourly wind speeds for whole years were extracted from data of the UK Meteorological Office [12] in 6 locations in Scotland. These wind speeds were then calculated at various altitudes according to the power law profile methodology defined in [13], in order to have the wind speed at the wind turbine altitude.

Step 2: the potential electricity produced by a 2.6 MW turbine (Vestas© V100 model) $P_{T,t}$ [in MWh/hour] was then calculated, using the wind turbine power curve.

Step 3: the local hourly demand over a year in Scotland D_t [in GW] was estimated based on data published by the University of Edinburgh [14].

Step 4: each series was divided by its average over a year so that they were comparable as shown in Figure 1 below. The difference Δ between the normalized hourly electricity production $P_{T,t}$ and the normalized hourly average demand D_t was then calculated.

Step 5: the curtailment levels WC [in %] was calculated by adapting the methodology from [11] to the UK case. These levels were calculated according to the wind penetrations Φ_W [in %] announced by the UK government from 2011 to 2030 and the penetration limit PL [set to 30%], which is the maximum proportion of wind electricity that can be handled by network operators.

Step 6: finally the temporal distributions of curtailed wind electricity were calculated. All the vectors $(P_{T,t}, D_t)$ were ordered by decreasing values of the vector Δ instead of by date. The number of equivalent fully curtailed hours n^* was then calculated with equation (2).

$$n^* = \min\{n \in [\![1;8760]\!]\} \quad s.t. \sum_{t=1}^{n^*} P_{T,t} \geq WC \cdot \sum_{t=1}^{8760} P_{T,t} \tag{2}$$

The indices $t \in [\![1;n^*]\!]$ give the curtailment occurrences for the studied year (hour, date and type of day). Results and analysis are presented in Section 4. Figure 1 highlights the discrepancy observed between the average wind electricity produced (in red) and the range of average hourly demand (range from the minimum [summer weekend] and the maximum [winter weekday]).

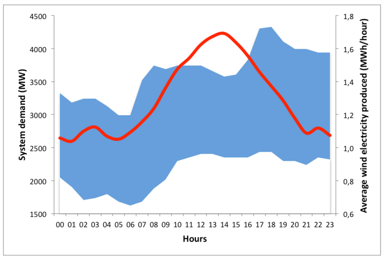

Figure 1: Comparison of the hourly average demand range and the hourly average wind electricity produced

Model 2: Assessment of the two schemes

These results were then used to assess the two schemes' capability to cover wind intermittency. Figure 2 presents the overall methodology employed.

The model inputs are the wind curtailment temporal distributions calculated in Model 1 for 2011, 2015, 2020, 2025 and 2030; the electrolyser operational data [6]; the battery electric vehicles operational data [15, 16]; the balancing services data (prices and volumes per category) extracted from trends from the National Grid; general data (hydrogen and public electricity prices). All these data are evolving within years based on official data [3].

The model outputs were of three types: the lifetime economic results (the total value, the total revenue and the total cost of the scheme in £ over its lifetime), yearly payments results (for each operational year: total payments divided in utilisation payments, availability payments and hydrogen payments) and balancing results (share of otherwise curtailed energy used, energy specifically used for balancing services). As a reminder, balancing services are being paid through two mechanisms: a payment for the ability to change its electrical output (availability) and a payment for actually changing its output (utilisation payments). Results of this model are presented in section 5.

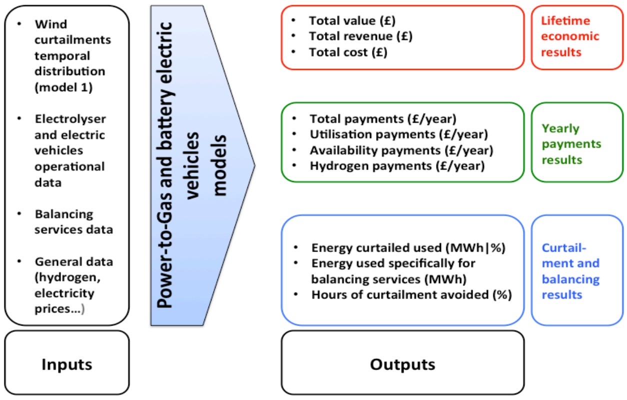

Figure 2: Overview of the methodology employed to assess the two schemes [3]

It is also noteworthy to mention the operational schedules selected for both schemes. Regarding the P2G concept, the electrolyser was assumed to be working full-capacity (capacity of 2.6 MW) everyday from 00:00 to 07:59, to be working half-capacity during weekends and bank days from 08:00 to 16:59 and not working for the remaining time schedules. These choices were made to optimize the balancing services provided while not using too much 'dirty' electricity from the public grid. The BEV scheme aggregated 433 medium-sized electric vehicles (battery of 29.7 kWh of which only 80% is usable for flexible charging) in order to have a capacity corresponding to 2.6 MW. This industrial fleet of vehicles had a primary activity, keeping it busy Monday-Friday 08:00-20:00. The remaining period was divided into two period types: a first period (every day between 20:00 and 00:59; every weekend), during which each electric vehicle is idle ready to use otherwise curtailed energy to recharge its battery; a second period, (Monday-Friday: 01:00-07:59) during which the vehicle recharges its battery but the process can be interrupted to reduce demand if required.

4. WIND CURTAILMENTS RESULTS

It was found that the curtailment occurrences were initially concentrated in the early summer morning during weekends. However, as the years pass and the amount of curtailed energy increases, these distributions become more balanced between seasons, types of day and even hours. Figure 2 illustrates the increased amount of curtailed wind energy over time (2.a) and shows the change in hourly curtailments distributions found between 2011 (concentrated) and 2030 (more dispersed). The number of fully curtailed hours goes indeed from 16 hours in 2011 to 1,280 hours in 2030. According to our model, in 2011 all the curtailments occur during the early morning between 03:00 and 08:59. In 2020, curtailments occur with a better-distributed pattern between 01:00 and 17:59, with still few curtailments occurring during the peak electricity period 18:00-00:59. But in 2030, the amount of curtailed energy is so significant that curtailments can occur at every hour.

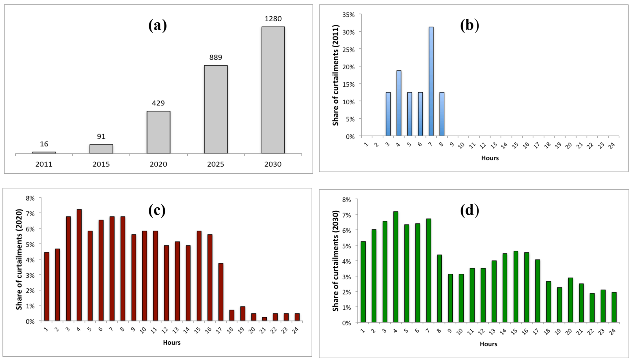

Figure 3: Hourly curtailments distribution results: (a) Number of fully curtailed hours (2011-2030); (b), (c), (d) Hourly curtailment distributions for 2011, 2020, 2030.

An analysis per season was also performed and it was found that initially, in 2011, almost all the curtailments occurred during summer, mainly because the electricity demand is lower at this period. But as soon as the curtailments levels WC are substantial – by 2020 – the probability of occurrence is more or less the same between seasons.

Finally an analysis per type of day (weekend or weekday) was conducted. It was found that most curtailments occur during the weekend even if the trend shades off as the years go by. An interesting feature of the analysis is that the concentration pattern proves to be persistent during weekdays (between 00:00 and 07:59), even in 2030.

Overall, these results suggest that the wind intermittency burden would be easier to cover for DNOs in the future due to a lower concentration pattern, allowing potential investments to be more extensively used and profitable. Nevertheless the curtailments effect should not be further disregarded because happening all the time.

5. ASSESSMENT OF THE TWO SCHEMES

This section presents the actual results found for the two schemes used separately: first the performances found for the return on investment and the share of curtailed energy criteria, second the payment structure of the two schemes.

Comparison of the two schemes' performances

It was found that the BEV scheme showed better performances in the medium-to-long term while the P2G concept was more appropriate in the early stage, as highlighted in Figure 4. The return on investment (ROI) comparison shows that economic results are initially extremely low for the BEV scheme ($ROI = 4\%$ compared to 26% for the P2G scheme). But the BEV's return on investment increases at a quicker pace, mainly due to predicted strong battery cost decreases. Both schemes show an identical ROI by 2017 (52%) and the BEV scheme becomes economically attractive by 2020 ($ROI = 100\%$) without any public subsidy. In 2030 the ROIs are respectively 235% for the BEV scheme and 170% for the P2G scheme. However the P2G concept has a strong advantage: it is very flexible in sizes and operational schedules and it can be deployed almost anywhere, and most notably near remote wind farms.

For the 'share of curtailed energy used' criterion, the P2G scheme seems more adapted in the early stage but the two schemes achieve very similar performances (between 65% and 73%) from 2020 to 2030. As a reminder, the amount of curtailed energy is not significant before 2020 in the model developed. It was nevertheless found that the two schemes had complementary performances regarding the occurrences day type. More precisely, the P2G concept seemed to perform better for curtailments occurring during weekdays whereas the BEV scheme appeared more appropriate for weekend curtailments.

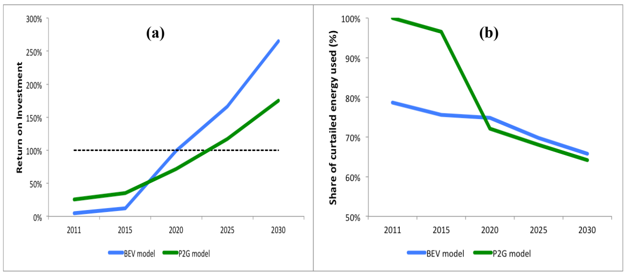

Figure 4: (a) ROI comparison; (b) Share of curtailed energy used comparison **ROI=Return on Investment; BEV=Battery Electric Vehicles; P2G=Power-to-Gas.*

Analysis of the payment structure

It is also interesting to focus on the payment structure of the two schemes; a structure divided between availability payments, utilisation payments and hydrogen payments (only for the P2G concept). The different sources of electricity used (public grid and otherwise curtailed electricity) are also investigated.

Figure 5 presents the yearly payments structure according to the year. For both schemes, availability payments represent the bulk of the revenues in the first years and appear stable or slightly growing over the years. The utilisation payments are initially minor (11% for the P2G scheme and 25% for the BEV scheme) but are predominant by 2020 and are clearly the major revenue source in 2030 (64% and 76% respectively). The power-to-gas concept also benefits from hydrogen payments, which remain minor in proportions (between 16 and 18%) but increase faster than the availability payments in absolute terms. The two concepts' business model is clearly based on the utilisation services and the provision of balancing services while using otherwise curtailed energy. This is a clear distinction with numerous conventional concepts developed for current balancing services, for which availability payments are predominant.

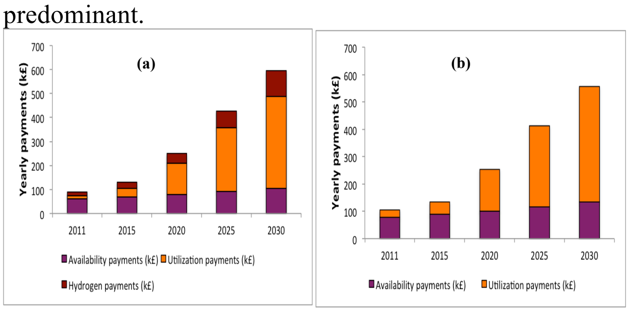

Figure 5: Yearly payments distribution for (a) the power-to-gas scheme; (b) the battery electric vehicles scheme

Finally Figure 6 shows the different electricity sources used in both schemes. Initially the two schemes' economic rationale relies on specifically provided balancing services, using public grid electricity. But, as soon as the levels of curtailments increase, most of the electricity used comes from otherwise curtailed energy.

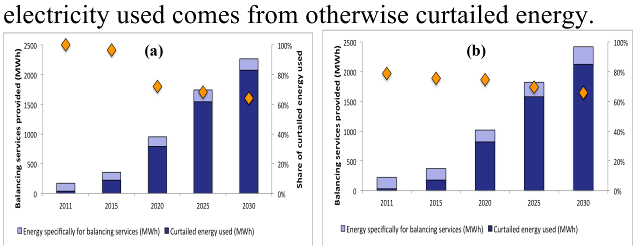

Figure 6: Balancing services provided per type of electricity source for (a) the P2G scheme; (b) the BEV scheme

6. CONCLUSION

This paper analyses the potential role of two modern schemes – the power-to-gas concept and an industrial fleet of battery electric vehicles – as a buffer against the issues raised by higher penetrations of intermittent wind energy in the UK. A time-based model, covering the period 2011-2030, was developed to compare the two concepts from the point of view of a DNO or a public investor, using economic and balancing services criteria. An estimation of the future wind curtailments distributions was realized: these curtailments are initially totally concentrated within specific periods of time (early weekend mornings during the summer) and quite moderate in their amounts; but they become much more equally spread as the years pass and the amount of curtailed energy dramatically increases. Regarding the two schemes' achievements, it was found that the battery electric vehicles scheme shows better performances – both in economic and balancing services terms – ten years from now but the scheme still remains prohibitively expensive in the early years. The power-to-gas concept offers the advantage to have better results in the short term and to be potentially deployed anywhere. These results suggest that DNOs and public investors should prepare themselves for the issues raised by renewable intermittency. This model has been applied to two specific concepts but can be used as a decision-support tool for other potential schemes. Further research in the field is required in order to better comprehend and prepare the solutions covering the issues related to higher penetrations of intermittent energy.

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