Modeling of electrolyzers in hydrogen vehicle refueling stations for provision of ancillary services

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Abstract — **Hydrogen vehicles offer the opportunity to use low-carbon fuel produced using electrolyzers, potentially from otherwise curtailed renewables, as a means to reduce the carbon intensive transport sector. Additionally, electrolyzers at hydrogen refueling stations (HRS), usually equipped with local hydrogen storage, could be used as a means of offering frequency control ancillary services (FCAS). In this paper, we introduce the modelling aspects of HRS that, while meeting hydrogen vehicle demand, could contribute to the provision of FCAS. To do so, a new unit commitment model that integrates hydrogen vehicle demand, power system operation requirements, and HRS has been specifically developed. Case studies performed on the Great Britain system show how the introduction of hydrogen refueling stations can contribute to the flexibility of the power system by providing reserve services and quantify the reduction in carbon impact of the transport sector.**

Keywords—hydrogen vehicles; electrolyzers; hydrogen storage; frequency control ancillary services; transport decarbonisation; unit commitment

List of acronyms

CCS	Carbon capture and storage
EV	Electric vehicle
FCAS	Frequency control ancillary services
FFR	Fast frequency response
GB	Great Britain
HFCV	Hydrogen fuel cell vehicles
HRS	Hydrogen refueling stations
PEM	Proton exchange membrane electrolyzer
PFR	Primary frequency response
QSS	Quasi-steady-state frequency
UC	Unit commitment
UK	United Kingdom

I. INTRODUCTION

In many countries, the transport sector is primary fossil-fuel based and, in particular for road transportation, the majority of vehicles run on petroleum fuels for which there is the associated problem of carbon emissions and air quality issues [1]. More recently, hydrogen fuel-cell vehicles (HFCV) have been introduced as a possible mean of reducing the road transport sector's emissions [2]. These vehicles carry a tank of hydrogen that acts as fuel that powers on-board fuel-cells. They refuel at hydrogen refueling stations (HRS) where hydrogen may be produced using electrolyzers that transform electricity into hydrogen. Each HRS has an integrated hydrogen storage facility which can store fuel for many hours before its delivery to the vehicles. Its utilization may be optimized with the electrolyzer operation to account for power system operational change. For example, its power consumption may be reduced in the presence of electricity price spikes or increased at times of excess generation from renewable energy sources. The full refueling of the HFCV takes only a few minutes; in fact, this fast refueling time and the decoupling of the refueling process from the power system offer key differences between HFCVs and electric vehicles (EVs) as the full recharge process in EVs may take a number of hours and require the power system to instantaneously meet charging requirements. Additionally, electrolyzers also have highly flexible technical characteristics, including fast ramps and response times, which mean that, in addition to providing clean fuel, they can potentially contribute to power system operation by offering frequency control ancillary services (FCAS) such as primary frequency response (PFR) and secondary and tertiary reserves. In a power system with a large penetration of non-synchronous variable renewable generation, such FCAS contributions may become very attractive as the system's needs develop and its requirements in terms of flexibility and frequency stability become more challenging. In particular, a substantial reduction in the generation level from conventional plants will lead to a reduction in the system's kinetic energy, potentially changing the PFR requirements, while the uncertainty and variability associated with renewable energy sources can lead to an increase in the system's secondary and tertiary reserve requirements.

To fully assess the role of HRS in integrating the transportation and power sector with consideration of the potential FCAS provision to the power system, 'multi-energy system' [3] [4] modelling tools need to be specifically developed accounting for the specific characteristics of a low-inertia power system. In particular, classical power system unit commitment (UC) modelling is required to be extended to assess the changes in the system inertia and frequency response and reserve requirements that accompany the increased penetration of variable generation. Meanwhile, the HRS modelling needs to account for the additional demand which would accompany the HFCV in the transport sector, the usage of the storage at the HRS, and the technical characteristics of the electrolyzers in offering FCAS to the power system.

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Prior research about the integration of hydrogen into the power sector has focused on the utilization of otherwise curtailed renewable generation for which the end-use of the hydrogen is as a low-grade combustible fuel, potentially injected into the natural gas network to displace natural gas [5] [6]. However, in that context, integration with the transport sector has yet to be explored. On the other hand, in [7] models were develped to assess the potential for expansion in wind farms to meet hydrogen demand for transportation; however, this was done without modelling of the integration with the power system. There is relevant work on evaluation of the system service requirements using UC modelling (see, for example, [8] [9] [10]), though without consideration of HRS to offer FCAS. Meanwhile, whole-system modelling tools to evaluate the system evolution (e.g., [11] [12]) do not capture the resolution required to assess FCAS needs or even day-to-day transportation requirements. Finally, the possibility of electrolyzers providing some power system reserve services has been investigated in [13], though at a very high level and without any technical or modelling details, or comprehensive analysis of multiple services.

In this work, an integrated unit commitment, hydrogen refueling station and transportation model has been developed to assess the potential benefits from the introduction of hydrogen vehicles. In particular, building upon the work in [8], a UC model incorporating system inertia modelling, primary frequency response, and secondary and tertiary reserves has been developed which includes HRS and transportation demand requirements. The UC model assesses the half-hourly generation by fuel type and the PFR and secondary and tertiary reserve contribution from both the conventional generators and the HRS, also taking into account the impact on system inertia. The ability of the HRS to provide different system services is modelled with consideration of its storage capacity and demand profiles.

Case studies are conducted on models based on potential future pathways for the Great Britain (GB) energy system in 2035. They are performed over a yearly timeframe and evaluate the shift of the provision of system services from conventional generators to HRS as well as the change in carbon content of the power and transport sectors as a consequence of additional renewable energy integration.

The remainder of this paper is structured as follows. Section II presents details on the modelling of the HRS and its integration with the UC model including the PFR and system reserve contributions as well as other aspects of the UC modelling. Section III presents the case studies and Section IV presents conclusions.

II. Modelling

A. Overall modelling

The modelling assesses the operation of the power system and the operation of the electrolyzers at the HRS, including the power system reserve requirements and provisions, over a yearly timeframe at half-hourly intervals. Therefore inputs include time series of power demand and renewable generation. Additionally, the formulation requires the half-hourly HRS hydrogen vehicle demand which is assessed via historical data derived from vehicle refueling stations sales with consideration for the growth in HFCVs and the seasonal variation in vehicle transportation. The integrated formulation evaluates the power system and HRS operation and lead to an evaluation of system costs, carbon emissions, reserve provisions, etc. Furthermore, post-analysis examines the system cost reductions through allowing the HRS electrolyzers to participate in the power system reserve provision. A summary of the model's inputs and outputs are presented in Fig. 1.

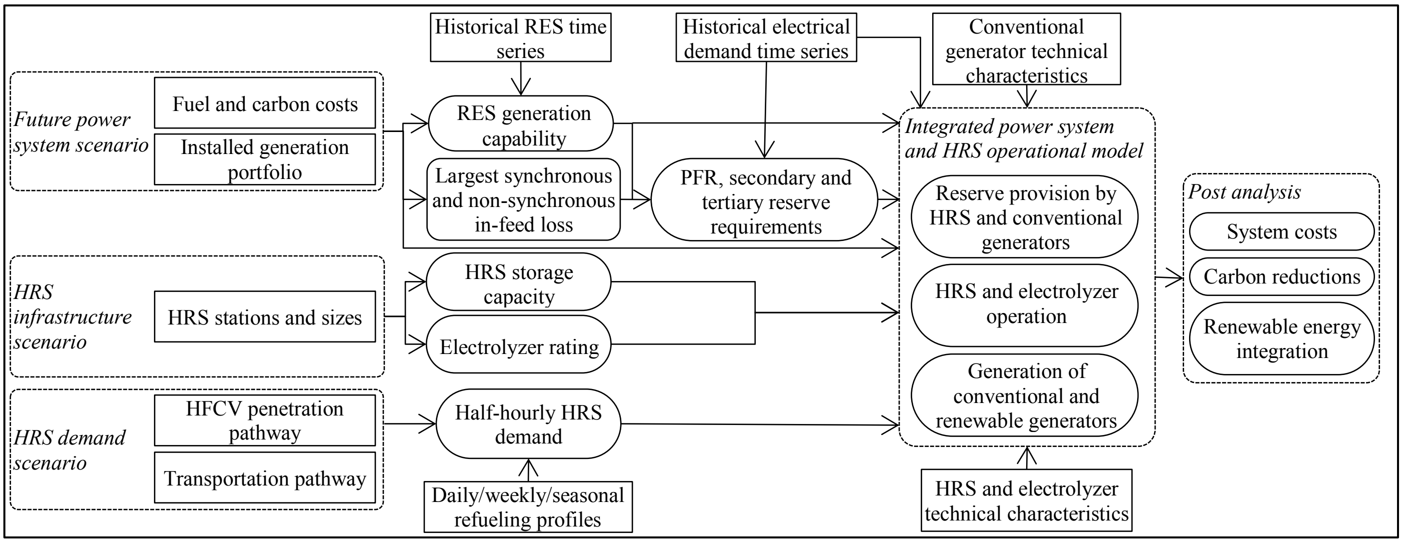

Fig. 1. Overall modelling methodology

B. Hydrogen refuelling stations (HRS) modelling

The HRS demand is driven by the future demand for hydrogen in the transportation sector. With consideration of the projected annual car and light-goods vehicle (LGV) vehicle-kilometres, V for a country (i.e., the total distance driven by all the cars and LGV within the country in a year), it is supposed that the fraction performed using a HFCV is ϕ_H. Then the annual demand for hydrogen is given by $V \cdot \phi_H / F$ where F is the vehicle fuel economy. This is combined with statistics describing the annual vehicle-kilometres by month, the weekly vehicle-kilometres by day, and the intraday vehicle refueling profiles to provide a system half-hourly HRS demand, $HD(t)$, over a year.

If the system hydrogen storage capacity of the HRS is given by $\overline{S}$ and the hydrogen in store at t is given by $S(t)$, then it is required that there must be a balance between the hydrogen created, the hydrogen consumed and the change in hydrogen in storage. I.e., for each time period t:

$$HD(t) \cdot \Delta T = \eta \cdot HP(t) \cdot \Delta \mathrm{T} + S(t-1) - S(t) \qquad (1)$$

where ΔT is the unit commitment time periods, $HP(t)$ is the system HRS power demand, and η is the efficiency of the electrolyzer (including additional auxiliary losses associated with the refueling process). For a HRS, the hydrogen in store is limited by its storage capacity while the power demand by the electrolyzer rating and its minimum load. So, if $\overline{HP}$ is the system rating for the electrolyzers and m_h is the minimum load of electrolyzers as a fraction of their capacity, then, for all t,

$$m_h \cdot \overline{HP} \leq HP(t) \leq \overline{HP} \qquad (2)$$

while the system store of hydrogen is limited by

$$0 \leq S(t) \leq \bar{S} \qquad (3)$$

The HRS have the ability to offer a number of reserve services to the power system. In this paper, provision of three upward reserve services will be considered, namely: PFR, secondary reserve and tertiary reserve. To each reserve class r is associated a time interval $[T_r^s, T_r^e)$ between the start T_r^s and end T_r^e of the reserve deployment after a contingency. For example, in the British power system, secondary reserve is required to respond 5 mins after an event and supply power until 15 mins after it [14]. The use of the HRS in providing upwards reserve to the power system requires that there is enough hydrogen in store that, should a contingency occur and the HRS respond, then the HRS demand should still be met. In the modelling, it has been assumed that the hydrogen utilization over the forthcoming is perfectly predictable and that storage operation considers the PFR, secondary and tertiary reserve contributions from the HRS. So that, if $RH^r(t)$ is the reserve provision to class r from the HRS at t then denoting by τ the time after a potential contingency where $\tau \in [0, \max(\{T_r^e | \, r \in \mathrm{RC}\})\,)$ and RC indexes the reserve classes, then the quantity of hydrogen in storage imposes the limit

$$\sum_r \int_0^\tau \chi_r(\tau') \cdot RH^r(t) \; d\tau' \leq S(t+\tau) \qquad (4)$$

where $\chi_r(\tau')$ is the characteristic function describing whether at time τ' the HRS reserve r is being deployed so that

$$\chi_r(\tau) = \begin{cases} 1 & \text{if } \tau \in [T_r^s, T_r^e) \\ 0 & \text{otherwise} \end{cases} \qquad (5)$$

The reserve services offered by the HRS has been integrated into the UC modelling considering the facilities' downward ramp capability which is limited by the minimum part-load operation and its current operating level. I.e., for $\tau \in [0, \max(\{T_r^e | \, r \in \mathrm{RC}\})\,)$ then

$$\sum_r \chi_r(\tau) \cdot RH^r(t) \leq HP(t+\tau) - m_h \cdot \overline{HP} \qquad (6)$$

C. Unit commitment modelling

The HRS modelling has been integrated into a unit commitment model specifically developed for an assessment of the flexibility requirements of a future power system [8]. The original UC model was developed to address computationally intensive tasks such as annual simulations at half-hourly resolution, Monte Carlo simulations, or expansion planning problems and allows for its application in, for example, assessing annual utilization levels in power systems with a large penetration of renewable energy sources. This was achieved through a judicious choice of simplifications and relaxations of a full UC problem which have been benchmarked against alternative UC formulations for speed and for accuracy.

With a focus on the UC model's application in assessing future power system flexibility requirements, it accounts for conventional generator constraints including startup/shutdown costs, minimum up/down times, minimum stable generation levels, etc. as well as storage operation.

In this work, the UC formulation of [8] has been extended further to consider an inertia related PFR assessment [9] which includes, in addition to the traditional PFR provided for by conventional generators, the contribution from electrolyzers. The deviation of system frequency $\Delta\omega(\tau; t)$ over the time τ following a contingency at t is calculated using the methodology of [15]. This methodology considers the differential equation describing the relation between the system frequency and system power supply and demand including the effect of the generator inertia and the load damping. The modelling considers the impact of the loss of the largest generating unit and, following such a contingency, the power system responds using technologies providing primary frequency response. If the response from conventional generation is $RP_G^{PFR}(\tau; t)$ and the response from the electrolyzer is $RH^{PFR}(\tau; t)$ then the response is required to be sufficient so that the variation of system frequency should satisfy two conditions. Firstly, the frequency at the nadir should not exceed the maximum frequency deviation allowance $\overline{\Delta\omega}$ and, secondly, the frequency should stabilize to a quasi-steady-state (QSS) before additional generation can restore it to the nominal system frequency. With regards to the nadir allowance, the modelling considers the frequency response deployment time from conventional generators and the frequency dead-band for PFR activation. This is used to define the frequency response requirement $SR^n(t)$ to maintain the maximum frequency deviation. The response provision from electrolyzers is considered as fast frequency response (FFR), which can be fully deployed before conventional generators start ramping, and the corresponding maximum response capacity of the electrolyzers is denoted as $RH^{PFR_m}(t)$. Since the formulation of [9] describes the response requirements by a non-linear equation, a piece-wise linearization method is applied upon integration into the UC model. The required PFR capacity $SR^{QSS}(t)$ needed to restore the frequency to QSS is evaluated with consideration of the maximum deviation of system frequency at QSS following the maximum synchronous infeed loss L_m, and of the real power demand $D(t)$. The response provision $RP_G^{PFR}(t)$ from each generator G and $RH^{PFR}(t)$ from the electrolyzers, is required to meet the nadir constraint and restoration to QSS, i.e.,

$$\max_{\tau\in[T_r^s,T_r^e)}\left(\sum_G RP_G^{PFR}(\tau;t)\right)\geq SR^n(t) \qquad (7)$$

$$\max_{\tau\in[T_r^s,T_r^e)}\left(\sum_G RP_G^{PFR}(\tau;t)\right)+RH^{PFR_m}(t)\geq SR^{QSS}(t) \qquad (8)$$

The modelling additionally accounts for the secondary and tertiary reserve requirements and their provision from different technologies. The system reserve requirements $SR^r(t)$ for class r at time t accounts for the outage of the largest generation unit and the uncertainty in the wind and solar generation. Its fulfillment from conventional generation sources considers the ramp rates and the available upwards generation capacity so that if the generation G has set point $P_G(t)$ then its provision $RP_G^r(t)$ for each reserve class r at t is limited by

$$\sum_r \chi_r(\tau)\cdot RP_G^r(t) \leq \overline{P_G}-P_G(t+\tau) \qquad (9)$$

where $\overline{P_G}$ is the installed capacity of generator class G and, again, τ is the time following a contingency. In addition, the reserve allocation is limited by the ramp capability of the generators so that for all τ

$$\sum_r \chi_r(\tau)\cdot RP_G^r(t)+\ P_G(t+\tau)-P_G(t)\leq RC_G\cdot\tau \qquad (10)$$

where RC_G is the (assumed constant) ramp capability of generator from class G.

The reserve provision requirement for each reserve class r is then described by

$$\sum_G RP_G^r(t)+RH^r(t)\geq SR^r(t) \qquad (11)$$

The UC has objective function minimizing the system operational costs while meeting the power demand and the demand for the hydrogen transportation sector (i.e., because of uncertainties in future HRS operation, any profits associated with the sale of hydrogen to the transportation sector have not been considered and the modelling has focused on the physical constraints on meeting the hydrogen demand). The costs considered include those associated with fuel, carbon tariffs, conventional generators starting up and shutting down, electrical load-shedding and over-generation.

The HRS demand is included with the power supply-demand balance equations in the formulation so that, if $P_G(t)$ is the real power output of generator G at time t, $P_S(t)$ is the real power charging rate (discharging is negative) of energy storage (e.g., pumped storage, etc.), $D(t)$ is the electrical demand not including the HRS then

$$\sum_G P_G(t)-\sum_S P_S(t)=D(t)+HP(t) \qquad (12)$$

where the summations are over the classes of generators G and storage units S.

The UC model has been applied to power systems with a large penetration of variable renewable generation (primarily wind and solar). These have been modelled using historical wind speeds and irradiance data which have been projected against a future generation portfolio.

III. CASE STUDIES

The methodology has been applied to case studies based on the British power system and transportation needs. In particular, the scenarios considered are based on the potential development of the energy system in 2035 and considers a large increase in the renewable generation penetration in the power system. They also consider an increase in the number of hydrogen vehicles, these pathways have been elaborated from those being developed by the Hydrogen Mobility Europe 2 (H2ME-2) project to assess the potential for hydrogen infrastructure in Europe. Before presenting results on the integration of HRS with the power system, key details will be presented to the scenarios considered.

A. Hydrogen refuelling station input data

The transportation scenario considers a program to reduce the emissions from the transportation sector by replacing Britain's diesel and petrol cars and LGVs with zero-carbon alternatives. Such pathways for Europe are presented in [16] and the 'Concerted Approach' pathway has been used as the foundation for those considered here to present a pathway similar to others considered in the UK [17] [18]. In the proposed scenario, it is assumed that, by 2035, ~4% of the British car and LGV vehicles are HFCVs. Because, compared to battery electric vehicles, HFCVs have a greater range (i.e., kilometers which may be travelled between refueling) then it is assumed that in the market for high annual utilization (above 20,000km/year) then HFCVs are the zero-carbon vehicle of choice. It is then the case that, in the proposed scenario, 5.2% of car and LGV vehicle-kilometers are driven using HFCVs. The future British road transportation needs follow 'Pathway 1' published by the Road Traffic Forecasts developed by the UK Department of Transport [19] and consider a 29% growth on the 2015 vehicle-kilometers by 2035. Based on feedback from HFCV trials, it assumed that owners of HFCVs will operate with similar refueling patterns to that which are currently followed at refueling stations. Data from historical aggregated refueling station sales by time of day and day of week from [20] have been used to develop a realistic representation for the system aggregated half-hourly demand profile for a year. These have been projected against the future HFCV roll out scenario and the annual demand for hydrogen by HFCV (as described in Section II.B) to develop the time series $HD(t)$. As the refueling follows user's lifestyle patterns, there is a diurnal nature to the profile which are presented for sample typical days from winter in Fig. 1. The system power capacity of the HRS is 1.25GW and the total hydrogen storage capacity is 27.5 GWh_{H2}. The efficiency of the HRS is taken as 75%. Results of field trials have shown that proton exchange membrane (PEM) electrolyzers may increase and decrease power consumption over their operating range within 0.2 secs [21]. Therefore, with the consideration of reserve requirements, no ramp restriction of the electrolyzers is imposed.

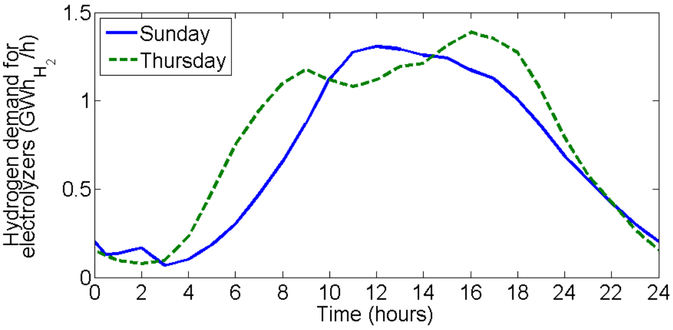

Fig. 2. Intraday fuel demand for a typical Thursday and Sunday from winter (elaborated from [20])

B. Power system input data

The power system scenario considered is based on that provided by the British electrical transmission system operator and considers a progression to a low-carbon power sector for which coal without carbon capture and storage (CCS) has been phased out of the generation mix and there is an increase in the carbon emissions price which is taken as £35.9/tonne. There has also been a large growth in the level of renewable generation with 48GW of wind and 35GW of solar installed [22]. The breakdown of technologies considered is presented in Table I as a fraction of the total installed capacity of 162GW. With a focus on the ability of the generators in providing reserve, each technology's upwards and downwards ramping capability has additionally been provided in Table I while further details on each technology's characteristics can be found in [8].

In the GB system, currently as well as in future generation projections, all the solar generation lies in the distribution network, the majority on roof tops. Because the transmission system operator does not have direct control over many of these generating units, then, in comparison to the transmission level wind generation, curtailment becomes administratively and, in some cases, technologically, more difficult. Hence, in the modelling, so as to successfully mimic the future system operation, an additional penalty has been associated with the solar curtailment so that solar generation is prioritized over wind generation.

TABLE I. INSTALLED GENERATION CAPACITY AND RAMPING CAPABILITY [22] [8]

Technology	Installed capacity (%)	Upwards/downwards ramp capability in half-hour
Nuclear	11.3	3%/2%
CCGT	13.4	60%/100%
Coal CSS	1.7	40%/67%
CCGT CCS	2.8	60%/100%
Biomass	2.2	40%/67%
Wind	29.3	-
Solar	21.0	-
Storage (inc. pumped storage & batteries)	2.9	
Interconnector	14.2	100%/100%

C. Impact of introduction of HFCV

Simulations have been conducted to analyze the impact of HRS and HFCV on the operation of the power and transportation sectors. The 'HRS' scenario considers the presented power, HFCV and HRS infrastructure though without the HRS electrolyzers providing reserve services. This is compared against a Business as Usual ('BaU') scenario which considers a transport sector without HFCV. Table II shows the utilization level of each technology and, because of the additional demand arising due to the HFCVs, there is an increase in the total level of generation in the 'HRS' case. However, there is a change in the breakdown of the generation as this additional generation is primarily fulfilled through the clean fuel sources of wind and nuclear as well as cheap electricity imported through interconnectors without system inertia contribution.

TABLE II. GENERATED ENERGY BEFORE AND AFTER THE INTRODUCTION OF HCFV AND HRS INFRASTRUCTURE

Technology	Annual generation (TWh/year)		
	BaU	HRS	Difference
Nuclear	112.28	115.57	2.9%
CCGT	53.53	54.09	1.0%
Coal CSS	11.36	11.64	2.5%
CCGT CCS	16.17	16.16	−0.0%
Biomass	14.41	14.68	1.8%
Wind	79.94	83.10	3.8%
Solar	22.43	22.42	−0.0%
Pumped storage (inc. losses)	−2.63	−2.55	−3.2%
Import	36.60	41.04	12.1%
Total	344.09	356.15	3.5%

Compared to fossil fueled vehicles, HFCV do not have the associated carbon emissions, hence they can lead to a reduction of the carbon impact of the transport sector. The emissions of hydrogen fuel cell vehicles and the electric vehicles (which, in the considered scenarios, following [22], account for 13.9% of the car vehicle-kilometers and has been included with the power system demand) have been accounted for in the generation emissions. Table III presents the power and transport sectors' carbon emissions for each scenario (any carbon intensity associated with interconnector imports has not been included) and it can be seen how the introduction of

HFCV infrastructure leads to a 3.3% reduction in emissions in the power and transport sector.

TABLE III. CARBON INTENSITY OF POWER AND TRANSPORT (CAR AND LGV) SECTORS

	Carbon emissions (Mtonnes CO_2e / year)		
	Power sector	**Cars and LGV**	**Power and transport sector**
BaU	30.8	56.9	87.7
HRS	31.1	53.7	84.8
Difference	1%	−5.6%	−3.3%

D. Contribution of HRS to power system reserve services

The potential of electrolyzers to contribute to power system reserve has been evaluated through consideration of the 'HRS' scenario of Section III.C which has been compared against the 'HRS+FCAS' scenario in which the full formulation of Section II is utilized and the HRS provide power system reserve services. Fig. 2 presents the reserve contribution of different technology types to the power system and show how, with the introduction of HFCV and HRS infrastructure there is a reduction in the amount of conventional plant required to provide reserve. In Fig. 2, 44%, 7% and 0.2% of PFR, secondary and tertiary up reserve can be contributed by HRS, which reduces the reserve provision burden of conventional generators and storage. This has a substantial impact on generation levels and Table IV presents each generation technology's annual generation value. From the table it can be seen that the more expensive and carbon intensive CCGT generation reduces by 75.9%, while there is greater generation from the lower-carbon technologies of coal with CCS and biomass (49.5% and 16.7%, respectively); then, a 12.8% increase in nuclear generation further reduces the carbon intensity of the power system.

TABLE IV. GENERATED ENERGY WITH AND WITHOUT ELECTROLYZERS CONTRIBUTING TO POWER SYSTEM FCAS

Technology	Annual generation (TWh/year)		
	HRS	**HRS+FCAS**	**Difference**
Nuclear	115.57	130.35	12.8%
CCGT	54.09	13.06	−75.9%
Coal CSS	11.64	17.40	49.5%
CCGT CCS	16.16	15.94	−1.4%
Biomass	14.68	17.13	16.7%
Wind	83.09	82.49	−0.7%
Solar	22.42	22.44	0.1%
Pumped storage (inc. losses)	−2.55	−1.51	−40.8%
Import	41.04	58.85	43.4%

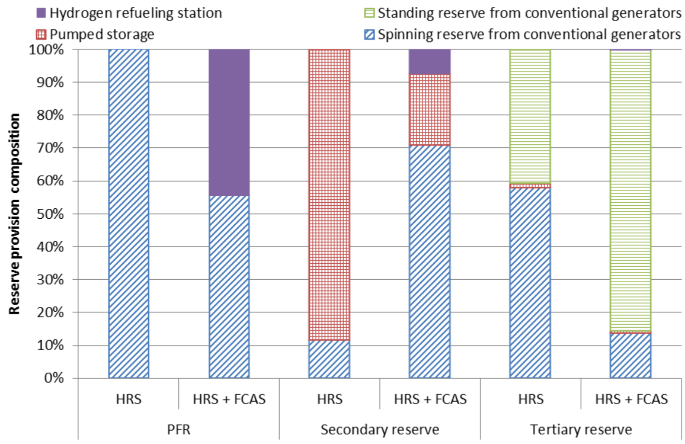

Fig. 3. Reserve composition for alternative technology types

As the HRS displaces the reserve provided for by conventional generating units, then this can lead to a reduction in the carbon emissions. Table V presents the results of the carbon intensity of the power system for each case and shows a 60.5% reduction in emissions and 18.8% reduction in operating costs.

TABLE V. REDUCTION IN CARBON INTENSITY AND COST OF THE POWER SECTOR WITH ELECTROLYZERS CONTRIBUTING TO FCAS

	HRS	HRS+FCAS	Difference
Carbon emissions (Mtonnes CO_2e / year)	31.1	12.3	−60.5%
Operating costs (£×10^9/ year)	5.84	4.74	−18.8%

IV. CONCLUSIONS

In this work a methodology has been presented which allows for the study of the operation of hydrogen refueling stations in meeting the demand of a hydrogen based transport sector while contributing to reserve for the power system. The modelling method of using electrolyzers to provide different ancillary services is introduced, which includes fast frequency response, primary frequency response and secondary and tertiary reserves. The use of hydrogen fuel cell vehicles and hydrogen refueling stations which use electrolyzers as a means to produce the transportation fuel allows for clean energy from renewable sources to be used in decarbonizing the transport sector. The introduction of HFCV allows for greater use of less inflexible, low-carbon generation technologies of nuclear, coal with CCS, and leads to a 3.3% reduction in the carbon intensity of the power and transport sectors. It has been shown how the hydrogen refueling station's storage coupled with the electrolyzers' fast ramping capability allow for the electrolyzers to contribute to power system ancillary services and this leads to a 60.5% reduction in the carbon emissions of the power sector. Ongoing work developing the model further will study system services provision from a portfolio of resources, e.g., batteries, wind turbines and photovoltaics, so that the system can be optimized to improve the integration of renewable generation and comparisons can be made as to the relative contribution from each of the relevant technologies.

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