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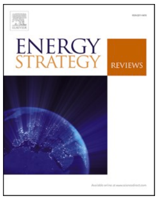

Effects on environmental impacts of introducing electric vehicle batteries as storage - A case study of the United Kingdom

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ABSTRACT

This paper examines the potential environmental impact of using electric vehicle batteries as storage in relation to an energy system as it moves towards the goal of net-zero emissions in 2050. The electrified transportation sector is an inevitable step towards a more sustainable energy system to meet climate change mitigation. Large-scale deployment of electric vehicles increases electricity demand whilst simultaneously presenting an opportunity to use electric vehicle batteries to shift peak demand through vehicle to grid, battery swapping, and reuse of retired electric vehicle batteries. The environmental consequence of using electric vehicle batteries as energy storage is analysed in the context of energy scenarios in 2050 in the United Kingdom. The results show that using an electric vehicle battery for energy storage through battery swapping can help decrease investigated environmental impacts; a further reduction can be achieved by using retired electric vehicle batteries. Using an electric vehicle battery for energy storage through a vehicle to grid mechanism has the potential to reduce environmental impacts if the impact of cycle degradation is minimal compared with calendar degradation. This balance is dependent upon the lithium-ion chemistry, temperature and mileage driven.

1. Introduction

Nearly 200 countries have signed up to the Paris agreement by 2020 [1]. In 2019, the United Kingdom (UK) became the first major economy to enact into law the commitment to be climate-neutral by 2050 [2]. In 2020, the European Union (EU) politically committed to be climate neutral by 2050 [3]. Transport caused 25% of total greenhouse gas (GHG) emissions in the EU in 2018 increasing from 15% in 1990 [4,5]. In the UK, 27% of GHG emissions come from transport, of which road transport accounts for over 90% [6]. Electrification is recognised as the most effective way to decarbonise the transportation sector globally [7]. Governments around the world have been taking action to decarbonise transportation at different levels. The EU commission supports deployments of charging infrastructure and subsidies for electric vehicles and the ban of fossil fuel cars is on the agenda [8]; China will aim to stop contributing to climate change and go carbon neutral by 2060 [9] and in the USA, the California banned on sale of cars based on fossil fuels by 2035 [10]. In China, more than 1.2 million EVs were sold in 2018, a 63% increase over 2017 sales and in the USA, more than 360 thousand EVs were sold in 2018, an 81% increase over 2017 sales. In India, EV sales are predicted to reach 30% for private cars, 70% for commercial cars, and 40% for buses by 2030 [11].

Whilst this study focuses on the UK as a case study for introducing EVs as an energy storage mechanism, the results can serve as a guide to other nations who are following a similar route to decarbonisation. The UK has been chosen as a case study since it is one of the leading nations with respect to decarbonising its energy supply with renewables committing in law to net-zero carbon by 2050. Thanks to the cost reduction of renewable electricity, particularly in the form of offshore wind and a carbon tax implementation [12,13], the share of renewable energy (RE) in UK electricity generation has increased from 6.0% to 29.1% and carbon emissions have reduced from 467 g/kWh in 2012 to 192 g/kWh in 2019 [14,15]. In July 2018, the UK government published its road to zero strategy, which sets out plans to reduce carbon emissions from vehicles already on the road, and drive the uptake of zero-emission cars, vans, and trucks. The impacts of adding EVs into the energy system are highly dependent on the electricity used for charging EV batteries [16]. Depending on energy system configurations, in a system with high renewable penetration or significant renewable curtailment, adding EVs can reduce environmental impact by replacing internal combustion engines when the EV batteries are powered by renewable electricity. In 2018, 131 thousand EVs were on the road in the UK, which was around

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0.4% of total private vehicles, whilst zero EVs were connected through V2G [17]. Uptake is rising with a ban on the sale of fossil fuel cars and vans from 2035 suggesting all vehicles will be electric by 2050 to meet the target of net-zero emissions [18].

Whilst EVs have a large role to play in demand-side response, this study focuses on EV batteries as energy carriers, which can improve the integration of RE into the electricity grid by feeding energy back into the grid. Notably, EVs that are connected to the grid could be used in electricity storage in emergencies or extreme supply shortages, to supply power to the grid. This application is known as vehicle to grid (V2G). The term has mainly been used to describe using the power from the battery whilst it is still in the car. This study also considers the use of the battery during battery swapping (BS). Compared to V2G, battery swapping (BS) can offer a quicker and more convenient charging mechanism. At a BS service station, a robot can replace the drained battery with a fully charged spare within a couple of minutes. In 2013, Elon Musk demonstrated a sub-2-minute battery swap for a Tesla vehicle [19]. The commercial integration of BS is still at the early stage and China is leading implementation with over 187 battery-swap stations installed to support 16,000 electric taxis in 2020 [20]. Despite the early stage of implementation, BS is a battery management system that has the potential to meet drivers' requirements whilst providing significant storage flexibility to the grid as demonstrated [21,22]. The retired EV batteries can then be reused (RU) when they no longer meet EV performance standards, which is typically 60–80% of their initial capacity. With very few EVs reaching their end of life (EOL) in 2021, there is uncertainty about what the EOL capacity will be and will be dependent on, initial battery capacity, supply constraints and policy/social aspects driving the transition to electric vehicles. For the purposes of this article, we use EOL as 70% when we model battery degradation.

The concept of electric vehicles being able to provide power to the grid has been considered for more than 20 years with Nissan patenting (now expired) the concept in 2000 [23]. This was pursued in the US to make electric vehicles economic by providing revenue from V2G services [24], and more recently modelled with respect to the Spanish grid [25]. Much of the focus has been on how the support V2G can give to balance an energy grid with a high proportion of renewable energy [26]. This is also a focus in the work by Noel et al. who interviews experts about the advantages of EVs going beyond demand-side charging and include vehicle to home (V2H), emergency back up, and being supportive of future EV [27]. However, interviewed experts expressed some misgivings about the prospect of V2G with how much bi-directional charging would be of benefit due to battery ageing although there was no quantification undertaken. There have been many reports comparing the environmental impacts of EVs with fossil fuel vehicles in particular with respect to carbon emissions [28]. The carbon emissions due to EVs are not only acknowledged to be lower than those emitted by fossil fuel vehicles but have significant potential to reduce their emissions per kilometre travelled as energy systems across the globe reduce their use of fossil fuels [29].

The holy grail of sustainable V2G is if the materials resources (and other associated emissions) of an EV battery can be harnessed without detriment in order to avoid the creation of additional storage to support a zero-carbon grid. The effect of cycle life on battery degradation is the key parameter of how large a role V2G will have useful application in the future. To determine this experimentally is problematic since battery technology is moving forward quickly and to do real time experiments which complete at end of life can take 8 years plus. Projects such as the UK Electric Nation V2G project (https://electricnation.org.uk/resources/v2g-project/) are key to validate modelling but they have yet to complete and draw conclusions. These projects are not only evaluating the technical issues around V2G but also social issues such as, "will this type of service inconvenience the car owner?''

Currently we must rely on models that in the most case have been developed using both empirical and theoretical calculations [30]. These models consider both calendar life and cycle life of the battery. An Arrhenius relationship is the most commonly used method to model the effect of temperature on calendar lifetime of a battery [31–34], with temperature and time being the key variables influencing calendar capacity loss, dominated by lithium diffusion [34]. State of charge (SOC) is another effect which requires further integration of electrochemical ageing data with machine learning from large data sets to further improve the current models [35]. Hoog et al. [36] experimentally determined that whilst SOC contributed significantly to calendar fade at temperatures of 35 °C or above, at temperatures of 25 °C there was a minimal difference in calendar degradation between 50% and 80% state of charge. Cycle life is affected by depth of discharge, charge/discharge rate, temperature, and number of cycles.

This study evaluates for the first time the potential environmental consequences of introducing EV batteries as energy storage by V2G and BS whilst considering the environmental impacts during battery production and battery operation including the effect of battery degradation. To do so, the potential environmental consequences of four battery mechanisms of V2G, BS, RU, and battery stationary storage (BSS) are analysed as methods to provide storage for the electricity grid. These 4 storage service mechanisms are compared in the Future Energy Scenario (FES 2019) developed by the UK national grid [17]. Life cycle assessment (LCA) is employed to conduct the embodied environmental impacts as well as the impacts of in-use energy of battery grid service in the selected scenarios. In section 2, the method of life cycle assessment (LCA) is described. The assessed scenarios and assumptions are elaborated. In section 3, impact results of assessed scenarios are presented and discussed. Two lithium-ion battery degradation models are compared. The conclusion is presented in section 4.

2. Methodology

2.1. Goal, scope, and functional unit

The goal of this study was to assess the potential environmental impacts of introducing EV batteries as energy storage to FES as proposed by the national grid [17]. The potential future electricity scenarios were selected based on a mix of electricity generation technologies. These electricity scenarios were compared using consequential LCA methodology. For comparison purposes, the functional unit of this study was defined as 1 kWh of electricity generated or delivered by each technology in the UK. This functional unit was chosen because of its importance in many LCA studies for other industries too.

2.2. Assessment approach

The overall approach used for carrying out the LCA included the following steps: (1) Identify electricity scenarios, which are based on available national energy strategies and political targets (e.g. regarding the share of wind power, solar energy, and storage technology). (2) Develop scenarios, which included electricity conversion and storage technologies. The focus is the integration of electrical energy storage into these scenarios. (3) Perform LCA of scenarios, which includes impacts from different electricity generations and battery applications.

2.2.1. Electricity scenarios

Two electricity scenarios were selected as the baseline scenario: (1) Scenarios 2018 (S_{2018}), (2) Scenario 2050 (S_{2050}) (2050 community renewable scenario) from FES 2019. The '2018' scenario was selected as a reference representing the current electricity supply primarily based on fossil resources. Data for the electricity generation were based on the UK national statistics [37]. Electricity scenarios representing 2050 were associated with significant reductions in fossil-based electricity generation and increasing electricity generation from RE. With the increasing use of RE in electricity generation, more capacity of energy storage technologies is predicted to be installed, mainly pump hydro storage (PHS), batteries (BSS and V2G) with a small share of compressed air energy storage (CAES) and liquid air energy storage (LAES). For the purposes of this study the term battery capacity refers to battery energy capacity with units of Wh. A summary of electricity generation provided by all the technologies and fuels is presented in Table 1. The future electricity scenarios were designed to electrify the UK energy system, which means when the future electricity system satisfies not just current electricity demand but the energy demand for transportation and heating. The annual electricity demand was 307 TWh in 2018, which is predicted to increase to 453 TWh in 2050 [17]. It should be noted that the annual CO_2 emissions are 165 Mt from the energy sector in 2050 whilst meeting the government's 2018 target of 80% reduction of CO_2 emissions compared with 1990, no longer meets the tighter net-zero target [17,38] and further actions are required to meet the UK's legal commitments.

2.2.2. Lithium-ion battery chemistry

EV battery chemistries are usually different to batteries purchased for the sole purpose of stationary storage (BSS), since in the former fast charging and energy density are important factors whilst cost/longevity is the overriding performance criteria in the latter. The FES 2019 does not distinguish between different LIB chemistry within its analysis. However, LIB chemistry can affect the environmental impact due to different manufacturing impacts and different degradation mechanisms. Of the different lithium-ion chemistries used in EVs, batteries with lithium nickel manganese cobalt anodes (denoted NMC type) are the most widely used across automotive manufacturers including BMW, Nissan, and Chevrolet [39]. The ratios of NMC to each other are denoted by the numbers following such that NMC111 has an equal ratio of nickel, manganese, and cobalt [40]. Whilst other ratios are becoming more common such as 622, with nickel favoured over manganese and cobalt other aspects of cell make-up are similar. NMC111 was chosen for this study due to the availability of the detailed LCA and lifetime data enabled by its more mature market status. Stationary storage can also use NMC111, this market is small compared to the mobile market. For stationary energy storage, the total efficiency of grid application is set to be 71.6% for the support of the grid frequency by providing or receiving electricity to/from the grid [41]. Lithium iron phosphate (LFP) is the most used for BSS, The remanufacturing of batteries for stationary use requires less than 10% of the energy of the original battery manufacture [42,43]. The impact of equipment/infrastructure needed for the EV system are not included, as the impacts of these facilities are relatively small and are not the focus of the current study (e.g. battery swapping serve station, the inverter, of chargers, etc.).

Table 1
Annual electricity production of different generation technologies in the scenarios of 2018 and 2050 [17,37] Unit: TWh.

Resource	Technology	S_{2018}	S_{2050}
Coal	Coal-fired power plant (Coal PP)	10.10	0
Natural gas	Combined cycle gas technology (Gas CCGT)	115.01	1.03
	Open Cycle Gas technology (Gas OCGT)	0.12	0.47
	Gas combine heat and power (Gas CHP)	4.73	5.11
	Onsite gas power plant (Gas onsite)	2.28	0.27
	Gas power plant with reciprocating engine (Gas reciprocation)	0.79	1.50
Biomass	Biomass-fired power plant (Biomass PP)	20.42	2.63
	Waste incineration power plant (Waste PP)	4.46	3.50
	Combine heat and power (Biomass CHP)	1.97	12.48
	Combine heat and power (Waste CHP)	2.41	2.97
Diesel	Diesel-fired power plant (Diesel PP)	0.47	0
Hydro power	Hydro power	5.56	7.17
Tidal	Tidal power	0.004	3.13
Wind	Wind offshore	27.61	175.58
	Wind onshore	27.97	92.90
Solar	Photovoltaic (Solar PV)	13.82	47.67
Other renewable	Other renewables (Other REs)	8.29	24.06
Nuclear	Nuclear power	58.04	53.77
Storage	Pumped Hydro storage (PHS)	2.19	6.17
	Compressed Air Energy Storage (CAES)	0	0.96
	Liquid Air Energy Storage (LAES)	0	0.44
	Battery Stationary Storage (BSS)	0.74	7.94
	Vehicle to grid (V2G)	0	2.78
	Fuel cells	0	0.003

Battery degradations of NMC 111 batteries used for EVs, V2G, BS, and RU, are calculated using the model developed by Wang et al. [32]. The cycle life part of the model was developed using conditions from 50% DOD empirical data. The calendar battery degradation is expressed as:

$$Q_{loss} = 14876 * \exp\left(-\frac{24.5kJ}{RT}\right) days^{0.5}$$

where R is 8.314 $Jmol^{-1}k^{-1}$, T is Kelvin.

The cycle capacity loss is expressed as:

$$Q_{loss} = \left(a * T^2 + b * T + c\right) * \exp[(d * T + e) * I_{rate}] * Ah_{throughput}$$

where a is 8.61E-6 1/Ah-K^2; b is −5.13E-3 1/Ah-K; c is 7.63E-1 1/Ah; d is −6.7e-3 1/K-(C-rate); e is 2.35 1/((C-rate); f is 14,876 1/$day^{1/2}$; I_{rate} is C-rate.

For the BSS which uses LFP batteries, calendar degradation and cycle degradation are calculated based on the model developed by from Schimpe et al. [44]. Details of this model are included in supplementary information (A).

2.2.3. Assessed scenarios

A number of assumptions were made to undertake the assessment:

1. Introducing different EV battery charging technologies and EV battery applications will not change the total electricity generation and consumption in the scenarios.
2. Self-discharge is the same between battery stationary storage (BSS) and EV batteries during storage time, and no consequential change in travel habits are assumed. The principal service of EVs is mobility, which means the overall transportation service should not be affected by additional services of EVs.

Based on FES2019, in 2050 (S_{2050}), the decarbonisation target is achieved in a decentralised energy strategy with 58% of electricity generation is decentralised and over 78% EVs engaged in smart vehicle charging, and 14% of EVs engaged in V2G [17]. V2G exploits the storage potential from on-board batteries via bidirectional power flows between the vehicle and the grid, which is determined by the on-board battery storage capacity [45]. In S_{2050}, BSS and V2G provide 7.94 TWh and 2.78 TWh respectively as shown in Table 2. There are 31.7 million EVs with a combined energy storage power capacity of 146 GW, 2.9 million of these are involved in V2G activities (FES 2019). Each V2G vehicle contributes on average 965 kWh a year to support the power grid, at a discharge rate of 7 kW discharging to the grid at an average of 2.6 kWh a day. In reality, these vehicles would be plugged in longer than this, but power would only be drawn when there was significant demand. The S_{V2G} is built by increasing the usage of the V2G vehicles from 2.6 kWh to 9.0 kWh a day – rather than peak shaving, this would be more of a balancing system and is a similar value to initial data gathered from trials which

Table 2
Electricity delivered by BSS and EV battery in the 5 assessed scenarios (S_{2018}, S_{2050}, S_{V2G}, S_{BS}, S_{RU}). unit: TWh.

Scenario	Electricity Demand	BSS	V2G	BS	RU
S_{2018}	306.98	0.74	0	0	0
S_{2050}	452.53	7.94	2.78	0	0
S_{V2G}	452.53	1.18	9.54	0	0
S_{BS}	452.53	7.55	0	3.18	0
S_{RU}	452.53	1.18	0	3.18	6.36

incorporated both V2G and vehicle to home (V2H) [46]. S_{BS} follows the same assumptions as S_{V2G} on engaged EVs but uses BS as the charge delivery mechanism rather than V2G. The BS system needs to maintain a minimum of 25% of the total battery capacity at BS station service to meet daily swap demand [47]. Maintaining the same participatory fleet size as S_{V2G}, at least 3.18 TWh of energy delivered is required at the BS station to support EVs on the road. The increased electricity delivered by EV batteries (whether V2G or BS) is assumed to replace the electricity delivered by BSS in S_{2050}. The scenarios are not contradictory for example an EV battery with the service of V2G can be used for battery swapping at a different time. A summary of the 5 modelled scenarios is given in Table 2. A further detailed electricity mix is given in supplementary information (B).

In Table 3 the EV battery full energy capacity is set at 40 kWh with 70% useable capacity, the average drive distance was assumed to be 40 km/day [48]. The total EV battery capacity loss is the sum of both cycle and calendar degradation. The working conditions of EVs make distinguishing between the two degradations difficult, for example, low battery temperature decreases calendar degradation but increases cycle degradation. The calendar capacity loss is higher in the first year and slows down as time progresses [49]. The capacity loss can be above 5% if the battery is held at a higher stage of charge (SOC) and storage temperatures in the first year [50]. In this study, EV battery degradation is calculated based on the model developed by Wang et al. described in section 2.2.2 [32]. The operation temperature is set at 15 °C when EVs are in use and the temperature is set at 10 °C when EV parked in the garage or public parking. A 7-kW charge/discharge speed is chosen to calculate cycle degradation. The cycle degradation is calculated to be 0.02% per cycle. Due to the various factors which influence battery lifetime, battery degradation will vary significantly even in the same model of car and battery configuration. In regions with lower temperature, calendar degradation is lower than EVs from warmer regions; the cycle degradation follows the opposition trend [49]. Under the same climate, driving styles and charging frequency can affect the EV battery state of health (SOH). Compared with aggressive driving, gentle driving can help prolong battery life [51,52].

Using the model, we calculate for the drive profile considered in Table 3 it takes 8 years for a 40 kWh EV battery to decrease to 70% of the initial designed capacity. The consequence of integrating V2G for the EV battery at a rate of 9 kWh a day is to accelerate the degradation of battery cycle life. Consequently, the lifetime of the EV battery decreases to 5 years with total cycle degradation of 12% with a V2G service of one cycle every other day. For stationary storage, the battery operation environment can be adjusted to ensure optimum conditions for battery longevity. The cycle life span for the stationary battery can range between 5000 to more than 10,000 cycles [53]. The battery from Samsung SDI claimed to have 6000 cycle life with little cycle loss under optimised conditions [54]. The difference in reported lifetime of lithium batteries could be due to the battery chemistries, battery design, use of battery. The lifetime of BSS in this study is calculated based on LFP battery using the model by Schimpe et al. [44] with storage temperature of 15 °C, depth of discharge (DOD) of 100%. The lifetime is calculated to be 36 years with one cycle per day [44] (see Appendix). In the BS scenario, the EV battery on board is assumed to be the same as the EV battery without grid service. The calendar capacity loss of EV battery is different to the model or experimental results due to dynamic environmental conditions and state of charge of an EV battery. It would be harder to achieve a optimise condition for an EV battery compared to a stationary storage battery. For the RU service, it is assumed the retired EV battery with 70% capacity remaining can be used as stationary storage until an endlife of 30% of initial battery capacity.

Table 3
Assumptions of the battery pack capacity, charge frequency, and end of service capacity used in the scenarios detailed in Table 2.

Assumption	Unit	EV battery	V2G	BS	BSS
Battery energy capacity	kWh	40	40	40	40
Battery chemistry		NMC	NMC	NMC	LFP
Degradation model		Wang et al. [32]			Schimpe et al. [44]
Charging frequency		Every 4 days	Every other day	Every other day	Every other day
Lifetime	Year	8	5	8	36
Capacity (end of 1st service)	kWh	28			
Capacity (end of RU service)	kWh	12			

2.3. Data collection

Life cycle inventory of electricity conversion and storage is based on Ecoinvent 3 using their key characteristics listed in Table 4 [55]. It should be noted that only the environmental impacts of electricity generated within the country, as listed in Table 1, are included. The import and export of electricity is not considered.

The EV LIB chemistry is Li-ion NMC111. The environmental impacts are based on a literature study [56]. The BSS battery is LFP type, the environmental impacts of LFP battery are based on a literature study [57].

2.4. Life cycle impact assessment

The life cycle impact assessment (LCIA) method of ReCiPe 2016 (H) is employed to analyse the potential environmental impacts associated with the various resource use and pollutant emissions [69]. The LCI results are converted to impact category indicators based on characterisation factor, which expressed the contribution of each LCI result to

Table 4
Efficiency and lifetime values of UK electricity sources from literature, and assumption.

Electricity conversion	Key parameters		Assumptions in this study
	Efficiency	Lifetime/ year	
Gas CCGT	55–61% [58] 54.7% [59] 58% [60]	35 [58]	Efficiency: 60% Lifetime: 35 years
Gas OCGT	36% [60]	35 [58]	Efficiency: 35% Lifetime: 35 years
Gas CHP	Micro CHP 70% [58] Micro CHP (electric efficiency 5–20%, total efficiency 75%) [61]	20 [58]	Efficiency: 75% Lifetime: 20 years
Gas CCS	47–60% [58,62] 41.9% [59] 50% [60]	35 [58]	Efficiency: 50% Lifetime: 35 years
Offshore wind	≥3 MW	25 [58] 20-25 [63]	Lifetime: 25 years
Onshore wind	1 MW -3MW	25 [58]	Lifetime: 25 years
Solar PV	3kWp	20 [58]	25 years
Nuclear PP	32% [49,58] 36% [60]	50 [58]	Efficiency: 35% Lifetime: 50 years
LIBs for EVs	80.2% [42]	10 [49] 3285 cycles [64]	70% of initial capacity
LIBs for Stationary	71.6% [42]	3650 cycles [65]	70% of initial capacity
CAES	52% [66] 47.6% [67]		Efficiency: 50% Lifetime: 35 years
PHS	70–85% [68]	40-60 [68]	Efficiency: 70% Lifetime 50 years

each indicator [70,71]. The impacts are addressed in midpoint impact categories which are: Climate change (GWP), expressed as kg CO_2 equivalents; Ozone depletion (ODP), expressed as kg CFC-11 equivalents; Photochemical ozone formation (POFP), expressed as kg NOx equivalents; Particulate matter formation (PMFP), expressed as kg $PM_{2.5}$ equivalents; Terrestrial acidification (TAP), expressed as kg SO_2 equivalents; Freshwater eutrophication (FEP), expressed as kg P equivalents; Marine eutrophication (MEP), expressed as kg N equivalents; Human toxicity (HTP), expressed as kg 1,4-DCB equivalents; (freshwater, terrestrial and marine) Ecotoxicity (ETP), expressed as kg 1,4-DCB equivalents; Mineral resource scarcity (MRSP), expressed as kg Cu equivalents; Fossil resource scarcity (FRSP), expressed as kg oil equivalents.

In the ReCiPe2016, the characterisation factor of POFP is expressed in NOx-eq., while in the literature, POFP is expressed in kg NMVOC-eq. The characterisation factors are 1 for both NMVOC and nitrogen oxides (NOx). Similarly, the impact of MRSP was expressed in kg Fe-eq production, which is expressed in kg Cu-eq production in ReCiPe 2016. The characterisation factor of Cu-eq is 16 times higher than Fe-eq [69,72].

3. Results and discussion

3.1. Technology comparison per unit generation

Fig. 1 shows the environmental life cycle impact results per kWh of electricity delivered from electricity generation technologies (both fossil fuels and renewable) and energy storage technologies. Different environmental profiles are observed by different technologies with no surprise, gas-fired energy technologies show higher impacts in GWP and FDP per unit of electricity generation especially for the low-efficiency gas power generation (gas onsite, gas reciprocation, and OCGT). Carbon capture and storage (CCS) can reduce GHG emissions from gas-fired power generation, but increases other impact categories of ODP, POFP, PMFP, TAP, etc. as the consequence of the energy and material consumption by CCS facilities. Biomass-fired power generation shows the highest impacts in HTP, followed by biomass CHP, waste power generation, and solar PV. Hydropower has the lowest impact in all the power conversion technologies, followed by wind power, especially offshore wind.

As storage technologies are used to store energy instead of generating electricity, the impacts from storage technologies include the input of electricity generated from a mix of onshore and offshore wind turbines. In many systems analysis the input electricity to the storage system is ignored to make accounting of electricity more straightforward. However, this avoids the issue that storage is not 100% efficient and therefore any storage can increase the emissions of the original energy input. In the storage group, CAES and PHS have lower impacts compared with battery storage. In this study, the EV battery is designed for mobility service, so the impacts of the EV battery are based on the potential electricity delivered to the vehicle. The service of electricity storage causes less useable capacity for mobility. Among three types of battery applications stationary storage shows the lowest impacts of all the impact categories, this is due to its longer cycle life and lower requirement of energy density.

When renewable generation and storage technologies replace electricity generated from fossil fuels, the impacts of electricity shift from higher GWP to higher HTP and ETP. This trend can be seen from Solar PV, batteries, and wind energy. The higher impacts are due to material consumption during the manufacturing process [73,74].

3.2. Scenario results

Wind and solar energy with energy storage balancing supply and demand are the main technologies in a low carbon FES. Fig. 2 shows potential environmental impacts to deliver 1 kWh electricity from the five electricity scenarios outlined in Table 2. The shares of solar energy and wind power (both offshore and onshore) increased from 18% to 5%–59% and 11% from 2018 to 2050, and the share of fossil fuels decreased from 43% down to 2% in the meantime. As a result of the installation of renewable energy technology and the phase-out of gas power plants, the comparative LCIA results show that the 2050 scenarios have significantly decreased in pollution-related environmental impact categories, such as GWP, ODP, POFP FEP, and TAP, while the high electricity generation from RE shows increasing HTP, ETP, MEP, and MRSP. Displacing fossil fuels through the deployment of wind and solar energy can reduce certain pollutants but increase the consumption of material resources.

The GWP is calculated to be 0.165 kg/kWh in the considered technologies (excluding coal) in S_{2018}, with 95% of emissions from gas-fired power generation. The carbon emissions are reduced to 0.029–0.036 kg/kWh in scenarios in 2050, more than 30% of these emissions are due to a small amount of gas-fired power generation, to comply with 2019 net-

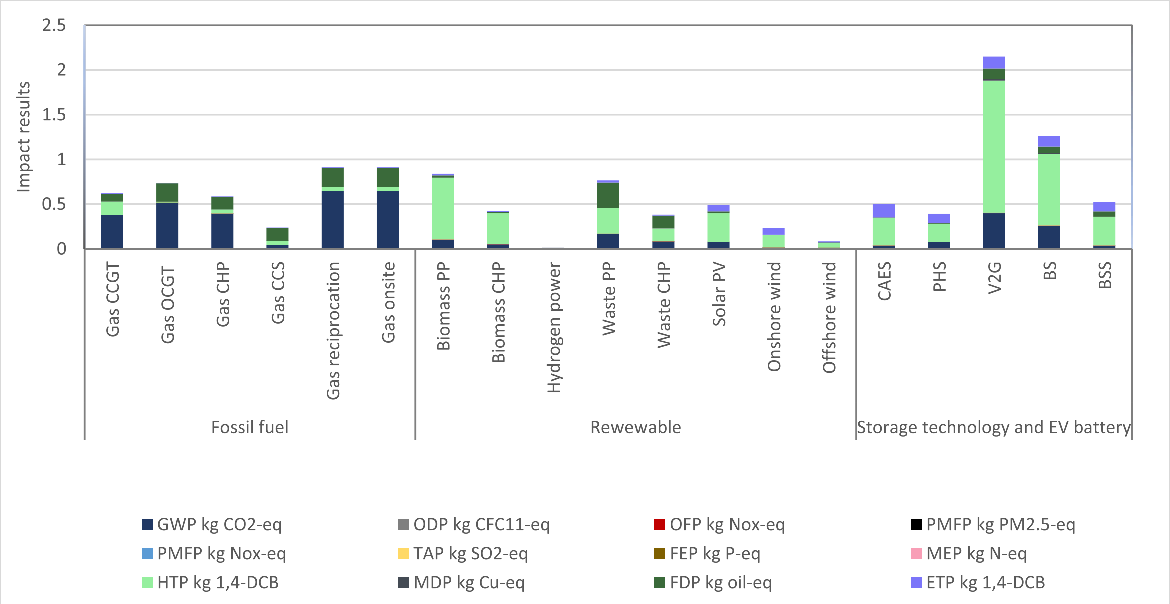

Fig. 1. Life cycle impact assessment result of 1 kWh electricity delivered from electricity generation and storage technologies listed in Table 1 as part of the FES2019.

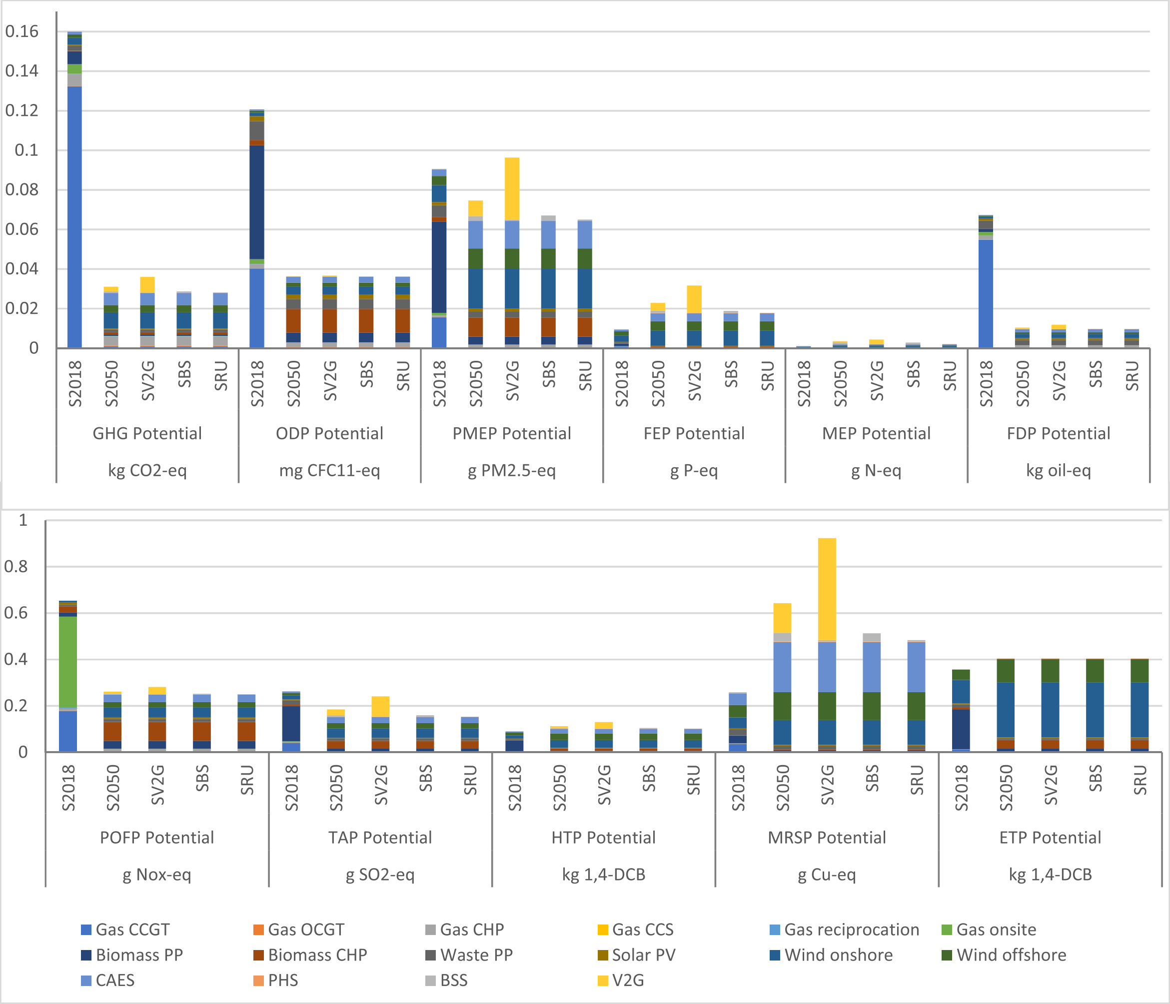

Fig. 2. Environmental impact of the 5 assessed scenarios (S_{2018}, S_{2050}, S_{V2G}, S_{BS}, S_{RU}) considered per kWh of electricity delivered (top graph at a smaller range to enable comparison of lower impact components).

zero legislation these will need to be fitted with CCS. Besides GWP, ODP is 3.3 times higher in S_{2018} than that in S_{2050}; POFP is 2.5 times higher; TAP is 1.2 times higher; FDP is 6.5 times higher. A major contribution to these impact categories is caused by gas-fired power generation. While S_{2050}, S_{V2G} S_{BS}, and S_{RU} have higher impacts of FEP, MEP, HTP, ETP, METP, and MRSP, which are 2.4 times, 3.2 times, 1.2 times, 1.1 times, and 2.5 times higher than these are in S_{2018} respectively. The major contribution to these impact categories is wind energy (both onshore and offshore).

The total electricity delivered by BSS and V2G is 10.7 TWh, which accounts for only 2% of total electricity generated in 2050. Even though the total capacity of EV battery is small compared with total electricity demand, the service of balancing the electricity system is significant to the future electricity market based on RE. In S_{V2G} GWP is calculated to be 0.036 kg/kWh which is 16% higher than that in S_{2050}, ODP is 0.9% higher, POFP is 7.6% higher, PMEP is 29% higher. TAP is 30.1% higher, FEP is 38.5% higher, MEP is 22.3% higher, HTP is 15.1% higher, MRSP is 43.5% higher, FDP is 14.0% higher, and ETP is 0.1% higher. Unlike in S_{V2G}, an overall reduction of the environmental impacts was achieved by replacing V2G with BS in S_{BS}. The environmental impacts can further decrease by using retired EV batteries for stationary storage applications in S_{RU}. MRSP is higher in scenarios in 2050 than that in S_{2018}. This is of interest because the required up-front investment in renewables required a combined material, which is non-renewable in general. The same reasons can also apply for the higher impacts caused by implementing V2G into the energy system. The impact results are higher than previous studies in scenario 2050 [75]. One of the reasons is due to assumptions of battery lifetime and potential proportion of BSS and V2G in the future scenario. Based on current technologies, only a limited reduction of impacts can be achieved by using retired EV batteries, and whilst the GWP of battery production is reducing as electricity grids reduce their GWP emissions reductions in material resources require focus on increased material recycling [29].

3.3. Sensitivity analysis

3.3.1. Uncertainty of battery lifetime

The biggest uncertainty in this analysis is battery lifetime. Currently the cycle life of an EV can be up to 3000 cycles depending on the different parameters [56,65], such as state of charge (SOC), charge rate, temperature and so on. Battery development for EVs has focussed both on increasing charge rate (which has the potential to reduce lifetime if all else is equal) and cycle life with the concept of a million mile EV accepted as technically achievable within the next few years [76] and with some EVs already reporting 500,000 km on a single battery pack [77].

Cycling ageing stress factors include operating temperature, DOD (%), middle state of charge (%), and number of full equivalent cycles. Calendar ageing stress factors include storage temperature, storage SOC (%), and storage time (days). All these factors are influencing the degradation of battery life. For large-scale energy storage, the annual degradation of LIBs was around 1% including both cycling and calendar capacity loss [78], increasing to 4% with 90% of SOC [50]. Different battery chemistries can have different degradation mechanisms and rates as shown by the study of Myall [79] where it took around 4.5 years for 24 kWh model LEAF (LiMnNiO chemistry) and 2 years for 30 kWh (NMC) to drop to 80% of initial battery capacity. Whilst the cause of this faster degradation was not explored, they did hypothesise that a longer time spent at a higher SOC could adversely affect the battery lifetime. An earlier V2G study suggested that even in an optimised scenario V2G services could reduce the battery life to 3 years before a replacement was needed [80]. Udin, Jackson et al. conducted a study using experimental data from $C_6/LiNiCoAlO_2$ (chemistry utilised by Tesla), Udin concluded that V2G in the correct conditions could reduce capacity fade by reducing the time that the vehicle spent at high states of charge, data used in the V2G optimal scenario [81].

3.3.2. Battery degradation model

The sensitivity of the results towards changes in driving charging frequency and degradation parameters was undertaken. The impact on battery life is not only determined by the amount of energy taken from the battery, but also by the specific state of charge of the battery during the V2G activity. To understand the effect of degradation models we compare the results using EV NMC model described in section 2.2.2 with a second battery degradation model.

The second degradation model based on lithium manganese oxide (LMO) chemistry as used by Nissan Leaf vehicles (24 kWh) demonstrates the effect of utilising a battery with improved cycle life compared with cycle ageing compared with NMC111. The cycle life part of the model was developed using conditions from 100% DOD empirical data [31].

$$Q_{loss} = \frac{\sum_m^C I(t_{m-}t_{m+1})}{I^* t_1}$$

where C is the cycling number of EV battery in one year to meet the travel demand. I is the charging current density, t_m is charging time needed in mth cycle.

The calendar degradation is the same as the model developed by Wang et. ac used for the NMC111 degradation calculations. The selected battery profile is illustrated below in Table 5. The EV battery capacity is assumed to be 40 kWh. The average temperature is assumed to be 15 °C for EVs and 10 °C for stationary battery storage. The charger rate is 7 kW for EV charging and discharging. Two EV battery degradation models are present as EV_1 and EV_2 respectively. The battery life time of EV_1 $V2G_{1a}$ and $V2G_{1b}$ are the calculated according to Wang et al. [32], The battery life time of EV_2 $V2G_{2a}$ and $V2G_{2b}$ are the calculated according to Yang et al. [31].

3.3.3. Battery charging profile

The principal of using V2G is to supply energy without affecting the transportation service for EV, therefore when the degradation of the battery causes a shortening of useable battery life the EV battery capacity is increased accordingly. Under this assumption, two scenarios of V2G frequency are developed for both EV1 and EV2 degradation models (Table 5). Two V2G charging frequencies are compared. $V2G_{1a}$ and $V2G_{2a}$ have the same charging frequency of every other day. The battery delivers more electricity to the power grid by increasing charging frequency to every day in $V2G_{1b}$ and $V2G_{2b}$. The consequence of increasing V2G use is to increase EV battery capacity to meet the daily drive distance of 40 km. The electricity from V2G replaces the electricity delivered from BSS which is assumed to be LFP battery. The reuse of battery retired from EVs is considered in all scenarios.

3.3.4. Sensitivity analysis results

The functional unit is to deliver 1 kWh electricity for transportation or electric grid support. Environmental impacts results are presented in Fig. 3.

The GWP are assessed to be 294 g $CO_{2\text{-eq}}$ and 181 g $CO_{2\text{-eq}}$, MRSP are assessed to be 16 g $Cu_{\text{-eq}}$ and 10 g $Cu_{\text{-eq}}$ in EV_1 and EV_2 scenarios. The reason for that is due to the lower cycle degradation in the EV_2 scenario. The EV battery lifetime increases from 8 year to 13 year in the EV_2 scenario. Compared with no V2G scenarios, V2G scenarios increase GWP and MRSP impacts due to the increasing battery capacity for transportation. V2G can help decrease the assessed impacts when considering substituted electricity both through V2G and reuse of EV batteries. With the current UK average daily drive distance and climate condition, environmental impacts, per kilometre driven, the overall GWP are assessed to be 106 g $CO_{2\text{-eq}}$, and 104 g $CO_{2\text{-eq}}$ in two V2G charging frequency based on the second battery degradation. In the scenarios based on the first battery degradation, the overall GWP are assessed to be 387 g $CO_{2\text{-eq}}$, and 653 g $CO_{2\text{-eq}}$. In the first battery degradation, the more use of V2G, the higher impacts of GWP are. In the second battery degradation model, the results are quite the opposite.

Even though increasing the daily use increased the battery cycle degradation the total electricity discharged for mobility service increases because the calendar degradation reduces due to a shorter lifetime. It should be highlighted that calendar fade is greater than cycle capacity fade, despite higher utilisation of EV batteries [82]. With the correct optimisation, there is an opportunity to store electricity in an EV battery to optimise cost, environment, and resource management whilst minimising the impact of capacity fade. V2G is still in the early stage of deployment, the consequence of a large scale of integration of V2G and its influence on both the electricity market and transportation sector will continue to be discussed whilst the transition to the renewable energy system is established at the same time. Vehicle battery modelling currently relies on large empirical data sets to create semi-empirical models which can then be utilised to predict battery lifetime in future scenarios. Where technology is developing batteries with lifetimes of many thousands of cycles and >10 years in calendar lifetime it takes significant time to collect the data to validate the models. Added to this battery chemistry and management systems are continually changing. Even within chemistries themselves NMC111 has been shown to have different (potentially more stable) ambient ageing characteristics to the more recently developed NMC811 [83]. Whilst it is tempting to think

Table 5

Key parameters of EV and V2G battery use conditions used for scenarios EV_1, EV_2, $V2G_{1a}$ and $V2G_{1b}$, $V2G_{2a}$ and $V2G_{2b}$.

	Unit	No V2G		V2G			
		EV_1	EV_2	$V2G_{1a}$	$V2G_{1b}$	$V2G_{2a}$	$V2G_{2b}$
Charging frequency		Every four days	Every four days	Every other day	Every day	Every other day	Every day
Battery energy capacity (required)	kWh	40	40	40 + 24	40 + 66	40 + 9	40 + 15
Drive distance	km/day	40	40	40	40	40	40
Lifetime	years	8	13	5	3	10	8
Capacity after of EV battery	kWh	28					
Battery capacity end of life	kWh	12					
Energy output for transportation	MWh	23.4	38.0	23.4	23.4	38.0	38.0
Energy output from V2G	MWh	0	0	23.4	26.3	38.0	113.9
Energy output from RU	MWh	74.5	220.8	118.9	199.3	287.0	358.7
Total Energy output	MWh	97.9	258.8	165.7	249.0	363.0	510.6

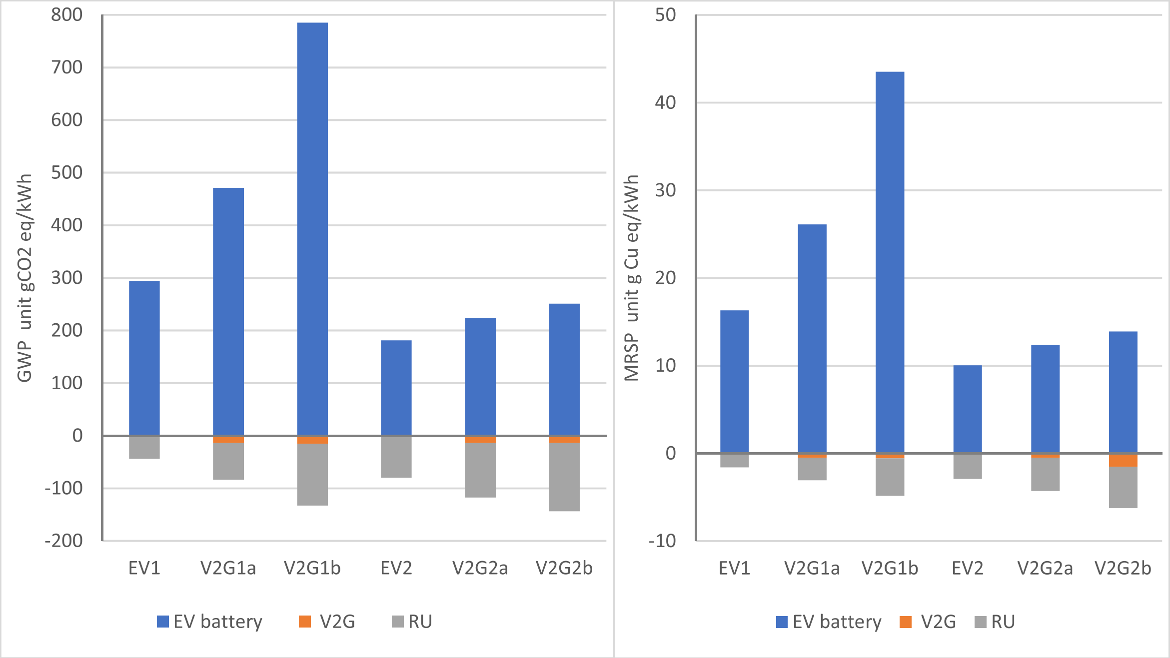

Fig. 3. Environmental impacts of GWP and MRSP from delivering 1 kWh electricity for EV mobility according two battery degradation model in 2050 energy scenario.

that developments in battery technology will lead to increases in battery lifetime this will only happen if this is a commercially attractive thing for the automakers to do. Demands of lower cost, higher energy density and faster charging rates could lead to the opposite trend. It is clear from the sensitivity analysis that if vehicle to grid is to be an environmentally beneficial option, then the impact of cycle degradation must be minimal compared with calendar degradation.

Given the sensitivity to temperature of the calendar degradation (regardless of specific chemistry), this will mean that local conditions are important as is the drive profile of the EV with V2G more beneficial in lower mileage scenarios.

4. Conclusion

This study analyses the potential environmental impacts of future electricity scenarios in particular relation to using vehicle batteries as energy storage compared with the electricity supply in 2018. It demonstrates that firstly, future electricity scenarios aim to reduce more than 95% of carbon dioxide emissions from 1 kWh electricity delivered. This results in higher materials depletion through the production of wind turbines, solar, and energy storage, which are needed to balance supply and demand. For this reason, vehicle to grid has been considered by the UK National grid, in their future energy scenario 2019, as a method of providing some of the required energy storage but without considering whole life emissions. This paper for the first time considers the effect of using vehicle batteries on the whole life emissions. The life cycle impact assessment results showed high levels of vehicle to grid use by an electric vehicle increased impacts of 11 investigated impact categories compared with using battery stationary storage, whereas lower levels of vehicle to grid support by the vehicle a day had lower impact per kilowatt-hour stored. The use of batteries as part of a battery swapping service system also has the potential to be a lower impact method of providing a vehicle to grid service, due to the potential to store the batteries in an optimum environment.

Whilst all drivers and scenarios are different it is particularly important to ensure that policy and financial structures are not developed that incentivise the driver towards a high number of kWh supplied or keeping the battery at a high state of charge, which could reduce the lifetime of the battery (particularly likely in vehicle to home scenarios). This is of even greater importance in countries where vehicles are likely to be stored in high ambient temperatures due to more severe battery degradation. Incentives should be targeted to prosumers with low mileage requirements, where vehicle to grid could even improve battery performance. Ongoing research to build more sophisticated degradation models as well as research into consumer behaviour are critical to maximise the benefits of using vehicle to grid as an energy storage system for a decarbonised energy system.

Credit author statement

Guangling Zhao: writing original draft preparation, data collection, calculation and conduct the analysis. Jenny Baker: Writing-reviewing and editing. Battery chemistry and degradation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Abbreviation

Battery Swap	BS
Battery Stationary Storage	BSS

Compressed Air Energy Storage	CAES
Combined Cycle Gas Technology	CCGT
Depth of Discharge	DOD
Ecotoxicity (freshwater, terrestrial and marine)	ETP
Electric Vehicle	EV
Freshwater eutrophication	FEP
Future Energy Scenarios 2019	FES2019
Fossil resource scarcity Potential	FRSP
Green House Gas Emissions	GHG
Global Warming Potential	GWP
Photochemical Ozone formation Potential	POFP
Human toxicity	HTP
Ionizing radiation	IRP
Liquid Air Energy Storage	LAES
Life Cycle Assessment	LCA
Marine eutrophication	MEP
Mineral resource scarcity	MRSP
Lithium-ion Battery	LIB
Nickel Cobalt Aluminium Lithium-Ion Battery	NCA
Nickel Manganese Cobalt Lithium-Ion Battery	NMC
Nitrogen Oxides	NOx
Open Cycle Gas Technology	OCGT
Ozone depletion	ODP
Pumped hydro storage	PHS
Particulate matter formation	PMFP
Photovoltaic	PV
Renewable Energy Sources	RES
Battery Reuse	RU
Scenario 2018	S_{2018}
Scenario community energy 2050	S_{2050}
State of Charge	SOC
State of Health	SOH
Terrestrial acidification	TAP
Vehicle to Grid	V2G

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