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Exploring the interaction between Renewables and Energy Storage for zero-carbon electricity systems

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Abstract

Many countries have set ambitious targets to achieve zero-carbon electricity systems by the Mid-21st Century. In their pathways, the renewable mix and the energy storage mix have been considered as two important facets. Current literature mostly focuses on how the storage mix is affected by the renewable mix, but few studied the inverse impact and the dynamic interaction between the storage and renewable mixes. We, therefore, developed an electricity system optimization model with hourly resolution to investigate how the interaction between renewable and storage mixes could accelerate the decarbonisation in future 30 years. This study considered the decarbonisation roadmap in the UK designed by the National Grid with variable factors such as cost structure of renewables and storages, annual investment budget, and load growth. Our research finds that short-duration energy storages with duration time at 6~8 h are preferred for providing cheap and rapid ramping power to meet the daily fluctuation in the early stage (2020-2030) of the decarbonisation process. In the late stage of retiring fossil fuels (2040-2050), high-share wind energy plus with long-duration storages (with duration time longer than 38 h) can solve the problem of great-quantity and long-lasting energy shortage caused by renewables, thereby achieving high-renewable penetration.

Keywords

Energy storages, long-term planning model, renewable energy integration, zero-carbon electricity systems

Highlights

Wind with long-term storage dominates in a carbon-free power system, while solar with short-term storage is modest

A proper mix of wind and solar and of short and long-term storage may enable an almost carbon neutral electricity system

National demand and climate patterns should be specified for the considered nation

As the world's largest contributor to CO_2 emissions at 40%[1], the power sector is going through a low-carbon transition by replacing fossil fuels with renewables. However, research shows that fully replacing the firm fossil generators requires an over-sizing renewable capacity, which comes at a prohibitively high cost[2]. Combining variable renewables with energy storage is widely recognized as a feasible solution for providing cost-competitive power with fossil fuels as the interaction between energy storage and renewables could be complementary[3,4].

The complementary nature between renewables and energy storage can be explained by the net-load fluctuations on different time scales. On the one hand, solar normally accounts for intraday and seasonal fluctuations, and wind power is typically variable from days to weeks[5]. Mixing the wind and solar in different degrees would introduce different proportions of short-term and long-term fluctuations in the net load curve. On the other hand, various energy storages address fluctuations across different timescales due to the technical and cost performance bias. For short-term imbalance caused by the intermittency of renewables, short-duration storages such as flywheels and lithium batteries are currently the most suitable for quick provision of high rated power[6,7]. For long-term imbalance triggered by seasonal variation of renewables, long-duration storages like pumped hydro storages (PHSs) and compressed-air energy storages (CAESs) are more suitable, because they can store large amounts of energy and slowly deliver it over days or even months[8-9]. An efficient combination of renewables and energy storage would enable the secure, reliable, and economic operation of a zero-carbon electricity system[10].

This interaction has a two-way effect while only one way has been investigated. Existing literature mostly focused on how to match the nature of renewables with the right portfolio of energy storage technologies, but is yet to answer the inverse question: how to adjust the renewable generation mix based on the operating cycle of energy storage (literature review is presented in the Supplementary Note 1). Existing studies[11-13] has investigated how the value of energy storage is affected by the renewable mix. Portfolio optimisation and cost assessments have been undertaken for different types of energy storages[14-16]. Other research[10,17,18] studied the optimal renewable mix in different regions, considering a fixed energy storage mix. However, there is a lack of insight in understanding how the energy storage mix affects the optimal renewable mix.

Taking the problem a step further, the dynamic evolution of the optimal portfolios of energy storage and renewables in the decarbonisation pathway still needs to be studied. Recent research indicates that, to integrate high proportion of renewables, the share of long-duration energy storage is supposed to dramatically increase in the near future[12,13,16]. Since the renewable mix is interactive with the energy storage mix, their optimal portfolios should also be time-varying over the zero-carbon transition period. This is different from previous research which aims to set a fixed optimal in a future year. It is this two-way and dynamic interaction that forms the key motivation of this research.

In this study, we aim to answer two overarching questions: (i) What is the optimal portfolios of renewables and energy storage considering the complete two-way interaction between renewables and energy storage? (ii) How do the optimal portfolios vary over time at different stages of the low-carbon transition? To answer these questions, an hourly electricity despatch model is developed to minimise the operation cost and carbon emission by dynamically adjusting the renewable mix and storage mix.

We let the W/S ratio (wind-to-solar ratio) denote the renewable mix, and the E/P ratio (energy-to-power ratio, see Methods and Supplementary Note 2) for the storage mix. The two ratios are reflected by the investment portfolio of storages and renewables and are used to constrain the hourly electricity despatch model. Four typical storage technologies, including batteries, PHS, CAES, and hydrogen, are considered in this study. To enable differentiated investment in energy capacity and power capacity， the capital expenditure of these storages is decoupled as energy-related cost and power-related cost, instead of assigning the duration time for each storage type.

Here, we take the UK as an example because the UK is taking a lead in the decarbonisation process with great data availability, integrity, and replicability[19]. We design a comparative study containing two decarbonisation pathways from 2020 to 2050 for the UK. The first pathway follows the Future Energy Scenario (FES) proposed by the UK National Grid which considers the E/P ratio and W/S ratio independently (Supplementary Figure 1-2). The other pathway, named the coordinated pathway, dynamically alters the investment in storages and renewables following an hourly optimisation model which simultaneously considers the E/P ratio and W/S ratio. To enable comparison, all other variables such as load growth, system expansion, and the projected investment scale of storages and renewables from 2020 to 2050 are kept the same based on the data from the Department for Business, Energy & Industrial Strategy (BEIS) in the UK[20,21]. Capital and operational expenditure cost of renewables and storages are considered separately and follow the future trend. Our research do not focus on the operation of a zero-carbon electric system, but instead on the optimal pathway that could theoretically maximise the usage of renewables and storages. (Practical constraints such as geographical, technical, and social-economic constraints are discussed in Discussion).

Model Assumptions and Validation

Due to various constraints, a number of technical assumptions are summarised in Supplementary Note 3. For networks, the uncertainty of future network topology and parameters makes it difficult to undertake a network constrained despatch model for the period of 2020-2050. Therefore, a macroscopical electricity despatch model is proposed for this study without considering the congestion in the network. It is a common assumption made by other research for decarbonisation pathway at the national level. For renewables, their hourly output cannot be accurately predicted over a long horizon (2020-2050). Here we follow a linear drift method adopted by Arbabzadeh et al.[Error! Reference source not found.] based on the renewable patterns in 2019 and the predicted renewable capacity by the National Grid[Error! Reference source not found.]. It is validated below that renewable pattern in 2019 are generally representative for the period 2015-2019. Other common assumptions such as a 10% energy loss and levelised cost are listed in Supplementary Table 2. This study does not consider the embodied carbon of the generation technologies, only their direct carbon emissions.

A benchmark study is undertaken to validate our model. Using the proposed model, we simulate the hourly despatch, generation mix, and carbon emissions from 2015 to 2019. The simulated results are then compared with real data published by the Digest of UK Energy Statistics (DUKES)[Error! Reference source not found.]. As shown in Figure 1, the outcome of generation mix in 2019 by our model is generally consistent with the real data. The differences are -2.8% in gas, -2.9% in wind and solar, 0.7% in bioenergy, 3.6% in hydro and 2.7% in nuclear. The comparison of annual carbon emission shows an average error of +/-5% between our simulation and the official facts over 2015-2019 as shown in Figure 2. The errors are generally low which gives us the confidence to extend the proposed model for future pathway studies (Other details are provided in Supplementary Note 4).

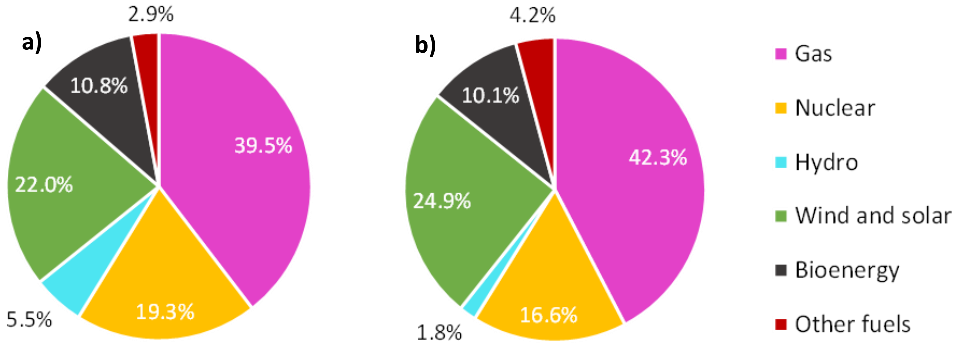

Figure.1 The annual electricity generation mix of different energy types in 2019; a) simulated results by our model; b) real data from statistics. Other fuels including hard coal, fossil oil, geothermal energy, and ocean energy.

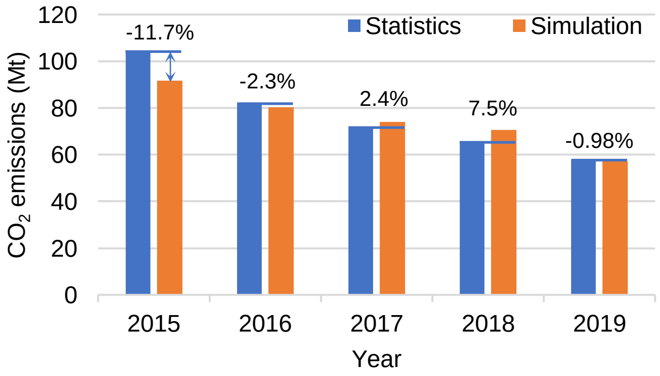

Figure.2 The annual carbon emissions from 2015 to 2019. The installed generation capacity is obtained from the Balancing Mechanism Reporting Service (BMRS). The installed energy and power capacity is obtained from the FES. The profiles of wind, solar, and load demand in 2015, 2016, 2017, and 2018 are derived based on the historical data in 2019 as described in Methods. These data are used as input for our model.

The pathway of coordinating the E/P ratio and W/S ratio.

Figure 3 shows the FES pathway and the coordinated pathway in terms of E/P ratio, W/S ratio, and annual carbon emissions from 2020 to 2050. The coordinated pathway invests more in long-duration storages and wind power, boosting the E/P ratio and the W/S ratio to 37:1 and 8:1 by 2050, respectively. By contrast, in the FES pathway, the E/P ratio decreases from 10:1 to 5:1 and the W/S ratio fluctuates around 2:1. This difference enables the coordinated pathway to reduce its carbon emissions to 0.16 Mt in 2050 while the FES pathway will still emit 6.46 Mt. Table 1 lists outcomes of the two pathways in 2050 with the same total investment of £ 96 billion but different portfolios. The coordinated pathway can significantly reduce accumulative carbon emission by 38% compared to the FES pathway.

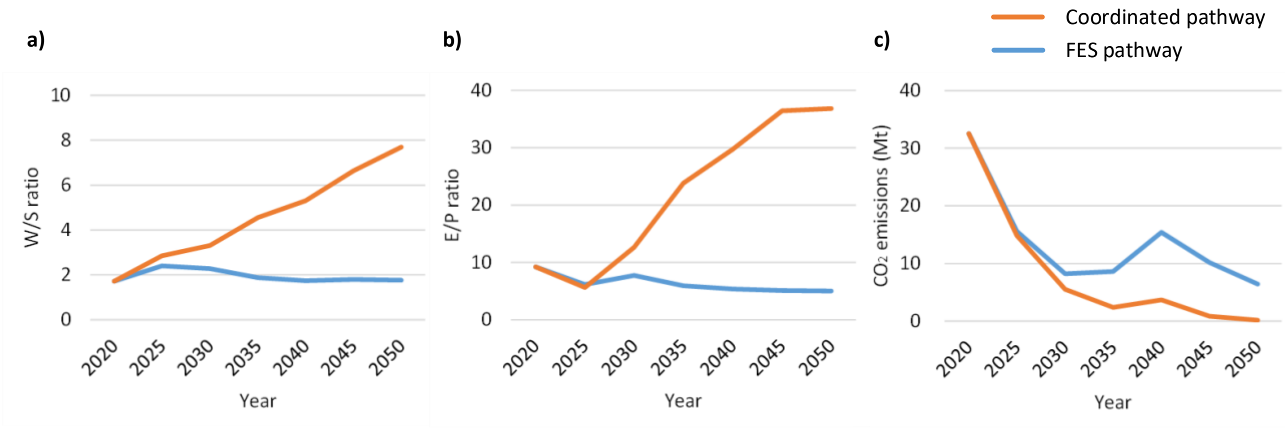

Figure.3 Two pathways towards a zero-carbon electricity system by 2050 in the UK; a) W/S ratio; b) E/P ratio; c) CO_2 emissions.

Table 1 | Characteristics of the UK's electricity system in 2050 following two pathways

Parameter	FES pathway	Coordinated pathway
Accumulative CO_2 by 2050 (Mt)	106.7	66.0
2050 annual CO_2 (Mt)	7.11	0.17
2050 CO_2 intensity (gCO_2/kWh)	43.5	1.04
W/S ratio in 2050	2:1	8:1
E/P ratio in 2050	5:1	37:1
Imbalance hour in 2050	1621	208
Maximum power shortage in 2050 (GW)	32.9	1.7

The imbalance hour is defined as the hours when total non-fossil generation including the output of storages, wind, and solar cannot meet the electricity demand.

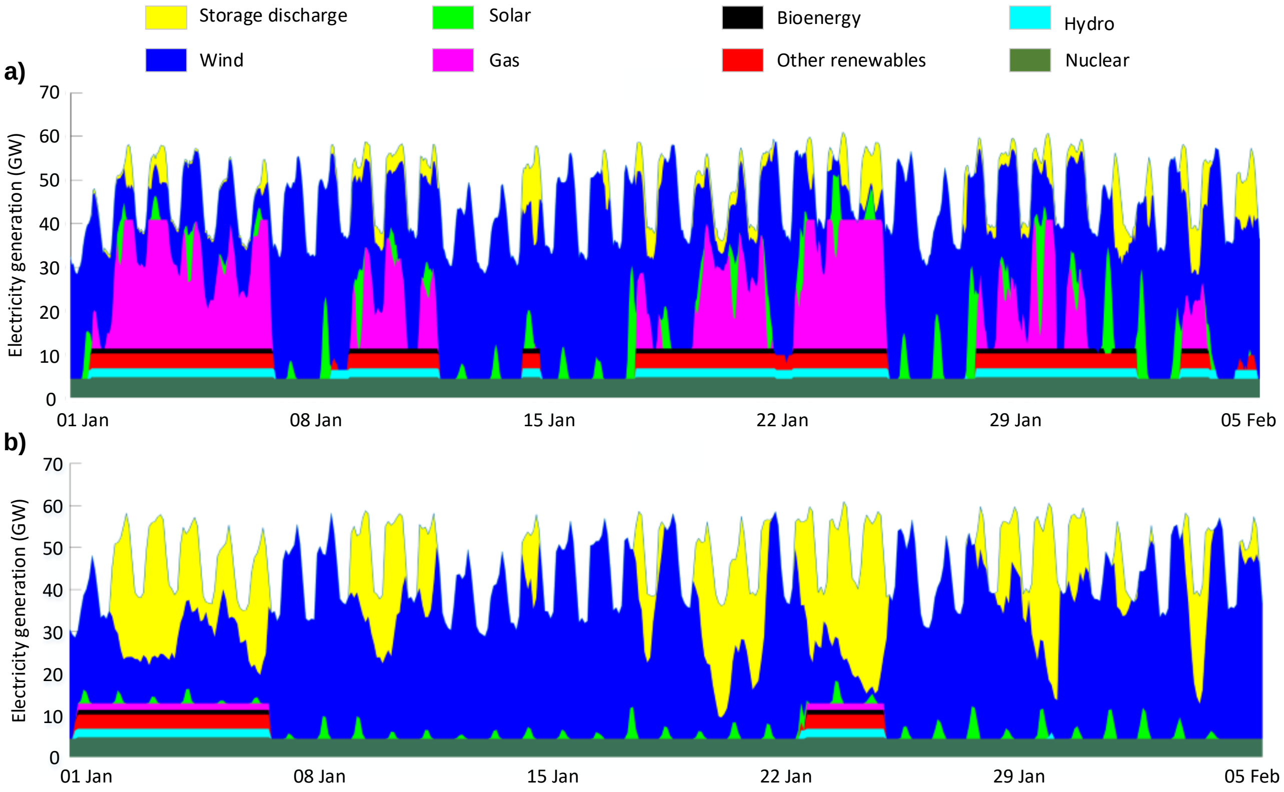

Figure.4 Hourly despatch outcome by fuel type for the first month in 2050 based on a) the FES pathway, b) the coordinated pathway. Due to the inefficient generation by wind and solar, the maximum energy shortage is estimated in winter 2050, which could last for a week with 2.7 TWh of total electricity shortage in the UK. In the FES pathway, At least 32.9 GW gas-fired generators are required to cover the energy shortage. In the coordinated pathway, the energy shortage is reduced by 18.5% to 2.2 TWh because of a higher share of

wind energy relative to the FES pathway. Deploying energy storages with 1.6 TWh energy capacity is able to reduce 98% of the energy shortage. 1.7 GW gas-fired generators are still required as backup energy resources for occasional shortage, leading to 0.16 Mt carbon emissions in 2050.

The FES pathway is expected to achieve zero carbon emission by 2050 based on the balance of annual electricity generation and consumption. However, when zooming in more granular time resolution, our hourly despatch model demonstrates that there will be as long as 1600 hours of imbalance in 2050. Most of the imbalance hours are concentrated between Nov-Feb because of the unavailable solar energy and unstable wind energy during this period (see Supplementary Figure 7). Even though £ 17 billion energy storages will be deployed by 2050, most of them are invested in short-duration storages such as batteries that have limited energy capacity. These short-duration storages are unable to cover a significant energy shortage at 12.3 TWh which must be powered by fossil fuel generators as shown by the gas generation in Figure 4-a for the first month in 2050.

If the UK adjusts its investment portfolio of renewables and energy storage according to the coordinated optimisation model, i.e., to increase the W/S ratio from 2:1 to 8:1 and E/P ratio from 5:1 to 37:1, the imbalance will be reduced to approximately 200 hours in 2050 as shown in Figure 4-b. The coordinated pathway prioritizes the combination of wind power and long-duration storages for the UK's electricity system. It is a sensible decision as the wind can produce 43% more electricity than solar in the UK with the same investment[Error! Reference source not found.](see Supplementary Figure 4). A drawback of higher penetration of wind is the strong seasonality of electricity generation. The issue can be exactly addressed by long-duration storages with large energy capacity and low energy-related cost.

In the coordinated pathway, more than 90% of the storage investment is planned for long-duration storages such as PHSs, CAESs, and hydrogen storage (see Supplementary Figure 8). This investment strategy enables the energy storage system to shift 44.2 TWh of energy in 2050 (amount to 13.6% of total electricity consumption) to cover the energy shortage when the wind stops blowing, as shown in Figure 4-b. Supplementary Figure 9 shows the behaviour of four types of storages among a year, where CAESs and hydrogen storages respond to monthly power shortage thus only performing about 10 charge/discharge circles among a year. PHSs are responsible for weekly power fluctuations and operate 80 circles a year on average. Batteries for intra-day power balancing run 1600 circles a year.

Coordination of renewables and energy storages

Table 2 | Carbon intensities of the UK electricity system in 2020, 2030, 2040, and 2050 following four pathways

Pathways	Description	Carbon intensity (gCO_2/kWh)			
		2020	2030	2040	2050
FES pathway	The E/P ratio and W/S ratio follow the FES	54.45	6.02	7.43	4.51
E/P optimised pathway	Optimising the E/P ratio only while the W/S ratio is held the same as that in the FES	54.23	5.98	4.87	0.69
W/S optimised pathway	Optimising the W/S ratio only while the E/P ratio is held the same as that in the FES	39.55	4.82	4.90	3.35
Coordinated pathway	Optimising the E/P ratio and W/S ratio simultaneously	39.51	4.43	2.24	0

This subsection takes a further look into the interaction of E/P ratio and W/S ratio. Figure 5 presents the carbon intensity with different combinations of E/P ratios and W/S ratios in 2020, 2030, 2040 and 2050. The yellow dot represents the position of the FES pathway and the red dot represents the outcome of the coordinated pathway. To better assess the impact of coordinated optimisation, we added another two pathways, the E/P optimised pathway (marked by the red square in Figure 5) and the W/S optimised pathway (marked by the red triangle in Figure 5), which optimise the E/P ratio and W/S ratio independently using the same hourly despatch model as shown in Table 2 (more details about the two scenarios are presented in Supplementary Figure 10-11).

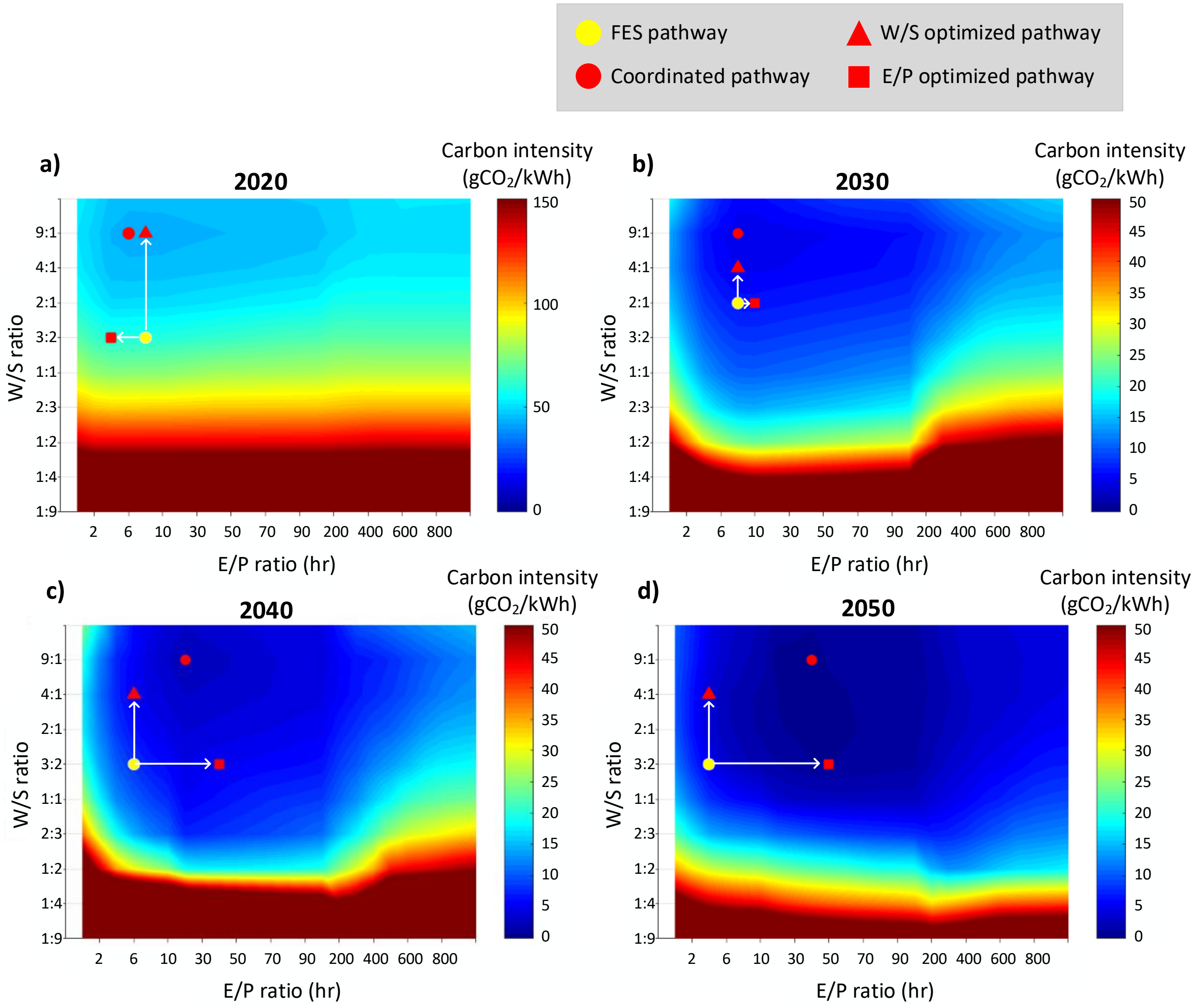

Figure.5 Carbon intensities of the UK electricity system under different E/P and W/S ratios in a) 2020, b) 2030, c) 2040 and d) 2050. ● marks out the minimum carbon intensity position calculated by

coordinated pathway. ● represents the position of the FES pathway, ▲ represents the W/S optimised pathway, and ■ represents the E/P optimised pathway.

The results show that all three optimised pathways can reduce carbon intensity compared with the FES pathway where the most significant reduction is achieved by the coordinated pathway over the period from 2020 to 2050. It is noted that optimising the W/S ratio can reduce more emissions in the early stage (i.e., 2020-2030) while increasing the E/P ratio has a significant effect on carbon reduction in the late stage (i.e., 2040-2050). It indicates that replacing fossil fuel generators with renewables can quickly reduce carbon emissions in the early stage but the marginal effect is diminished as the penetration of renewables increases. Long-duration storages are more preferred in a deeply decarbonised system to provide system balancing thus enabling the retirement of the final batch of fossil fuel generators.

It is observed that the optimal W/S ratio is constrained by the E/P ratio. In the W/S optimised pathway, the optimal W/S ratio is 9:1 in 2020s while decreasing to approximately 4:1 after 2030. This is because only in 2020 the number of fossil fuel generators can provide the flexibility to balance the seasonality of the dominated wind generation. As the decarbonisation progress accelerates in 2030-2050, fossil fuel generators will retire and the E/P ratio will gradually decrease from 10:1 to 5:1 as planned by the FES. The lack of long-term flexibility will limit the connection of high-share wind energy from 2030 to 2050.

Discussion

The fundamental finding behind this study is likely to be the compatibility between different renewables and energy storage technologies. When planning the E/P ratio and W/S ratio independently, this compatibility is usually overlooked thus leading to local optima. For instance, optimising the W/S ratio individually with an insufficient energy capacity of storages would limit the connection of wind power. Inversely, a low W/S ratio (e.g., 2:1 in the FES pathway) would lead to a magnified requirement in long-duration storages because high penetration of solar is unable to balance the system during wintertime.

For the UK's electricity system, our study suggests that shifting the investment towards long-duration storages over short-duration storages and wind energy over solar energy. According to the UK's government plan, the decarbonisation progress will be greatly accelerated after 2030 when the penetration of wind and solar sharply increase from 58.5% to 72.1% and storage investment will be tripled relative to 2025[Error! Reference source not found.]. Sufficient investment would provide a great opportunity for the UK to transfer to a wind-dominated electricity system with long-duration storages to overcome its seasonality. After 2030, the wind will receive most of the renewable investment and the energy storage investment share of long-duration storages such as PHS, CAES, and hydrogen storage will constantly increase (see Supplementary Figure 12).

In the early stage of the decarbonisation process, energy storages with low E/P ratio are preferred for providing cheap and rapid ramping power to meet the daily fluctuation thus providing advantages for integrating solar energy. Thus, there would still be a 12.5% growth of solar energy during 2020-

2030 in the UK In the late stage where fossil fuels are diminished, strong seasonality of variable renewables causes long-lasting and great-quantity energy shortage. Relative to the W/S ratio around 2:1 in the FES pathway, a greater W/S ratio at 8:1 can reduce the maximum energy shortage by 58% at the price of increasing the overall quantity of system imbalance by 6.5% relative to the FES pathway. Long-duration storages with an E/P ratio at 37:1 would significantly reduce 94.8% of energy shortage and maximise the usage of renewables.

It is noted that the recommended ratios may not be achievable in practice due to a range of geographical, technical, and social-economic constraints. Firstly, the development of offshore wind and long-term storage like hydropower heavily rely on natural resources, which are limited by local geographic conditions**Error! Reference source not found.**. Secondly, the marginal utilisation rate of renewables could be diminishing due to technical constraints such as network congestions and stability constraints. It is also understood that in a market-driven environment like the UK and many EU countries, it is difficult to directly control the W/S and E/P ratios. Instead, preferred investment is incentivised by policies and subsidies. Frequent changes of E/P and W/S ratios will challenge the stability of policies and cause market fluctuation. For policymakers in different countries with various constraints, the main implication of this paper is that the coordination of renewable mix and storage mix should be considered when making long-term plans and set up strong and consistent political and economic signals to steer the decarbonisation process along a potentially more cost-effective pathway.

Other parameters besides the renewable mix and storage mix might also bring impacts on our results. For examples, a number of studies show the system averaged generation cost is highly sensitive to the energy capacity cost of storages which must be lower than 14.8 £/kWh to be cost-competitive to fossil fuel generators and lower than 0.74 £/kWh to fully displace firm low-carbon generations (nuclear, bioenergy, hydro, geothermal, and other fossil fuels produced from low-carbon processes)[Error! Reference source not found.Error! Reference source not found.-Error! Reference source not found.24Error! Reference source not found.]. The 2050 average energy capacity cost of storages in our suggested pathway is around 2 £/kWh, close to the latter boundary. Most importantly, load profile and the renewable resources difference are key factors in determining the optimal system structure. Winter demand in the UK is higher than in summer, opposite to Italy and Spain with higher demands in summer. The temperate marine climate in the UK might also bring preference to the wind energy instead of solar energy. Therefore, our conclusions may suit the UK but are difficult to generalise.

For other countries with different variable nature of renewables, our methods can also be adopted to explore the optimal combination of renewables and storages that can maximise the penetration of renewables meanwhile minimise the system imbalance.

Methods

Economy evaluation of renewables and storages. We adopted the generation and storage cost projections revealed by BEIS to evaluate the UK’s spending on renewables and storages from 2020 to 2050[Error! Reference source not found.Error! Reference source not found.]. The cost of wind and solar is presented by the levelised-cost-of-electricity (LCOE) which is defined as the discounted lifetime cost of building and operating a generation asset[Error! Reference source not found.]. Here, we assume that the lifetime of wind and solar generations is 30 years. Thus, the capital investment in wind and solar is formulated as

$$InvRES_{yr} = Lt(C_{yr}^{\text{wind}} P_{yr}^{\text{wind,FES}} + C_{yr}^{\text{solar}} P_{yr}^{\text{solar,FES}}); \qquad (1)$$

where Lt is the lifetime of wind and solar in the unit of hour; C_{yr}^{wind} and C_{yr}^{solar} denote the capital expenditure (CAPEX) cost of wind and solar, respectively. The CAPEX cost refers to all relevant costs of building a generation or energy storage system, including pre-development costs, construction costs, and infrastructure costs. $P_{yr}^{\text{wind,FES}}$ and $P_{yr}^{\text{solar,FES}}$ are the installation capacity in the yrth year projected by the FES.

The capital investment of storages is decoupled into two aspects, power-related cost and energy-related cost**Error! Reference source not found.**. Limited by data availability, we have summarised the CAPEX cost of storage from a comprehensive literature review as shown in Supplementary Table 1. Based on the cost reduction projection from BEIS, we estimate the capital investment in energy storage by:

$$InvESS_{yr} = \sum_{s=1}^{ESS} C_{s,yr}^{\text{power}} P_{s,yr}^{\text{ESS,FES}} + \sum_{s=1}^{ESS} C_{s,yr}^{\text{energy}} Q_{s,yr}^{\text{ESS,FES}}; \qquad (2)$$

where C_{yr}^{power} and C_{yr}^{energy} refer to power-related and energy-related CAPEX cost of the ith storage technology in the yrth year; $P_{s,yr}^{\text{ESS,FES}}$ and $Q_{s,yr}^{\text{ESS,FES}}$ are the power capacity and energy capacity of the ith storage technology in the yrth year projected by the FES, respectively.

Modelling of wind and solar generation and electricity demand. We model the wind and solar generation and the electricity demand following the method presented by Arbabzadeh rt al.**Error! Reference source not found.** based on the UK historical data**Error! Reference source not found.**. We normalise the historical data of wind/solar/load by:

$$A_t^{\text{wind}}, A_t^{\text{solar}}, \text{ and } A_t^{\text{load}} = \frac{p_{2019,t}^{\text{wind}}}{P_{2019}^{\text{wind}}}, \frac{p_{2019,t}^{\text{solar}}}{P_{2019}^{\text{solar}}}, \text{ and } \frac{p_{2019,t}^{\text{load}}}{P_{2019}^{\text{max load}}}, \text{ respectively;} \tag{3}$$

where $p_{2019,t}^{\text{wind}}$, $p_{2019,t}^{\text{solar}}$, and $p_{2019,t}^{\text{load}}$ are the installed capacity of wind and solar and the electricity demand in the t^{th} hour in 2019, respectively; P_{2019}^{wind}, P_{2019}^{solar}, and $P_{2019}^{\text{Maxload}}$ refer to the installed capacity of wind and solar and the maximum electricity demand in 2019, respectively.

Optimisation model. According to the FES, energy resources are divided into natural gas, coal, nuclear, biomass, hydro, solar, wind, and other renewables. Pumped hydro energy storage, compressed air energy storage, hydrogen storage, and batteries are considered for energy storage technologies. We developed a linear capacity-planning and electricity despatch optimisation model with hourly time resolution to minimise the operation cost and carbon emissions of a macro-scale electric system, by dynamically adjusting the E/P and W/S ratio. The input data includes the energy mix, cost and investment data, and normalised profile of hourly demand, wind and solar generation. The outputs are the optimal power and energy capacities of energy storage, the installation capacity of wind and solar, and the hourly despatch of the electricity system.

There are two sets of decision variables in the proposed optimisation model, i.e., the capacity of renewables and energy storages, and the generation dispatch variables (Supplementary Note 2). In the FES pathway and the validation model where we try to simulate the actual operation of the UK electricity system, the capacity-related decision variables are set as constant parameters that follow the official data. The dispatch-related decision variables are optimised. In the coordinated pathway where we optimise the W/S ratio and the E/P ratio, the capacity-related variables and the dispatch-related variables are set as decision variables. In the W/S optimised pathway and the E/P optimised pathway, we individually let the capacity of renewables and the capacity of energy storages be the decision variables. Of course, the dispatch-related variables are also the decision variables.

The model related to the E/P ratio and W/S ratio is formulated as (other mathematical equations are presented in Supplementary Note 2):

obj. $$\min f = \sum_{t=1}^{T}\left[\sum_{g=1}^{Gen}(k_i^{\text{Gen}} + k_i^{\text{emission}})p_{i,t}^{\text{Gen}} + k^{\text{solar}} p_{i,t}^{\text{solar}} + k^{\text{wind}} p_{i,t}^{\text{wind}} + \sum_{s=1}^{ESS} k_i^{\text{ESS}}(p_{s,t}^{\text{ch}}\eta_{\text{ch},s} - p_{s,t}^{\text{disch}} / \eta_{\text{disch},s})\right] \tag{4}$$

s.t. $$Ratio_{\text{w/s},yr} = \frac{P_{yr}^{\text{wind}}}{P_{yr}^{\text{solar}}}; \tag{5}$$

$$p_{i,t}^{\text{wind}} \le A_t^{\text{wind}} P_{yr}^{\text{wind}}; \tag{6}$$

$$p_{i,t}^{\text{solar}} \le A_t^{\text{solar}} P_{yr}^{\text{solar}}; \tag{7}$$

$$Ratio_{\text{e/p},yr} = \frac{Q_{s,yr}^{\text{ESS}}}{P_{s,yr}^{\text{ESS}}}; \tag{8}$$

$$0 \le p_{s,t}^{\text{ch}} \le P_{s,yr}^{\text{ESS}} u_{s,t}^{\text{ch}}; \tag{9}$$

$$0 \le p_{s,t}^{\text{disch}} \le P_{s,yr}^{\text{ESS}} u_{s,t}^{\text{disch}}; \tag{10}$$

$$SoC_{s,t} = SoC_{s,t-\Delta t} + (p_{s,t-\Delta t}^{\text{ch}}\eta_{\text{ch},s} - p_{s,t-\Delta t}^{\text{disch}} / \eta_{\text{disch},s}) / P_{s,yr}^{\text{ESS}}; \tag{11}$$

$$SoC_{\min,s} \le SoC_{s,t} \le SoC_{\max,s}; \tag{12}$$

where the lowercase p refers to the hourly power output while the capital letter P is the installation capacity (P also refers to the power capacity in the case of energy storage); Q represents the energy capacity of energy storage; subscripts s, i, yr, and t refer to the serial number of storage type, generator type, year, and hour, respectively; $Ratio_{\text{e/p},yr}$ and $Ratio_{\text{w/s},yr}$ are the E/P ratio and W/S ratio; k_i^{Gen}, k_i^{emission}, k^{solar}, k^{wind}, and k_i^{ESS} denote the operational cost and carbon cost of generators, solar, wind, and storages, respectively; $\eta_{\text{ch},s}$ and $\eta_{\text{disch},s}$ are the charging and discharging efficiency factor of storages technology; $u_{s,t}^{\text{ch}}$ and $u_{s,t}^{\text{disch}}$ are binary variables to represent the state of storages (charging or discharging); $SoC_{s,t}$

denotes the state of charge of storages;

On the planning level, the capacity of wind and solar that is going to be installed is determined by the renewable investment amount and the W/S ratio as formulated by equations (1) and (5). The energy and power capacity of storages are decided by the storage investment amount and the E/P ratio as formulated by equations (2) and (8). These capacity variables further constrain the hourly operation of renewables and storages as formulated by equations (6), (7), and (9)-(12), thus affecting the objective function which is composed by operational costs of generators, renewables, and storages.

Data availability

The source data underlying Figures 1-5 are provided as a Source Data file. All data used for this study are available from corresponding authors upon request.

Code availability

The optimisation code based on MATLAB is available from corresponding authors upon request.

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Author contributions

D.C. and C.L. conceived the study. Y.L. and S.H. collected the experimental data and designed the model. D.C and R.L. performed the model evaluations. Q.W. and X.L. developed the data analysis and visualization. D.C. and C.L. drafted and finalized the manuscript. F.L., S.A., and B.Z. advised on the analysis and reviewed the manuscript. R.L., J. W. and S.A. revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/xxx.

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