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DISCUSSION PAPER

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Keywords: shadow prices, natural capital accounting, wind, renewable energy, asset valuation, welfare

JEL classification: D60, D62, E01, Q40, Q51, Q56

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Abstract

Shadow prices provide estimates of the economic contribution of capital assets (goods and services) to social welfare. They differ from exchange values in that they aim to incorporate the economic value of externalities associated with some assets. As the revised SNA25 standard explicitly recognises renewable energy resources as economic assets, this paper demonstrates an empirical methodology for estimating the shadow value of wind as a renewable energy asset, and provides estimates of the annual asset shadow value for onshore wind in the UK between 2009 and 2023. The estimates incorporate the value of avoided carbon emissions as a service wind energy provides. The estimated annual shadow asset values are much larger than market price equivalent asset values. While these estimates should be treated with caution due to a number of methodological choices involved, they signal the likely underestimation of the contribution of wind energy to social welfare. The paper concludes by discussing methodological assumptions and data needs for estimating shadow values. The paper provides a modest empirical contribution, whilst methodologically consistent with ONS natural capital accounting for feasible implementation.

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Introduction

Shadow values reflect the contribution of capital goods and services to social welfare (Coyle and Wdowin, 2025; Dasgupta, 2021). They differ from exchange values in that they aim to incorporate the economic value of externalities associated with assets and the services these provide, by estimating consumer surplus for example. Shadow value estimates are useful for a range of appraisal and evaluation purposes, as they provide complementary, or more comprehensive, information regarding social welfare than the market price equivalent valuations used in national accounting practice. Coyle and Wdowin (2025) provide a conceptual discussion of shadow prices understood as the marginal contribution of capital assets to social welfare; the aim of this paper is to demonstrate an empirical methodology for estimating shadow values in the context of a renewable energy asset, wind.[2]

The revised guidelines for national accounting in SNA25 strongly emphasise questions concerning whether the existing asset boundary comprehensively includes all the assets from which economic value flows. Consequently, the revisions include boundary extensions to, for example, the inclusion of data and renewable energy resources as assets. The full economic value generated from such capitals has hitherto not been accounted for in national accounts. It is, thus, also missing from metrics such as GDP.

A significant revision in SNA25 is the move to explicitly recognise and account for renewable energy assets such as solar, wind, and hydropower. Renewable energy assets are, thus, no longer 'missing'

[1] Bennett School of Public Policy, University of Cambridge. This research has been funded by the Office for National Statistics as part of the research programme of the Economic Statistics Centre of Excellence (ESCoE).
[2] Market equivalent values correspond to marginal private valuations, whilst in this paper we are concerned with estimates that correspond to marginal social values. As noted in Coyle and Wdowin (2025), these differ from average or total welfare measurements.

but, in line with national accounting principles, these are valued in terms of market price equivalents. These do not necessarily capture the full economic value in terms of social welfare, as they omit externalities. More generally, this wedge exists for any capital asset whose market price equivalent value deviates from its social welfare value. Shadow prices seek to capture the latter.

Wind, as a renewable energy asset, provides an example whose estimated shadow price may reasonably be expected to differ from its exchange value because of the presence of externalities. SNA25 revisions are to be implemented from 2030 by the UK Office for National Statistics (ONS), but currently, in the UK Natural Capital Accounts, the asset value of wind is based on the measurement of energy production (electricity generation) from wind power, using a resource rent approach. Physical flows of onshore and offshore wind and their market monetary value are recorded annually for the statistics for renewable electricity provisioning services.

However, a number of externalities are frequently attributed to wind-powered energy (Ramalho et al, 2025; Mattmann et al, 2016). In terms of positive externalities, these include reduced carbon emissions, or reduced fossil fuel dependence (Adeyeye et al, 2020; Ortega-Izquierda and del Rio, 2020); negative externalities include visual or noise pollution (Krekel and Zerrhan, 2017; Meyerhoff et al, 2010). Market price equivalents omit the value of these externalities.

This paper sets out a methodology for estimating the shadow value of wind as a renewable energy asset, as a demonstration for other assets involving externalities. We estimate the annual shadow asset value of onshore wind in the UK for 2009-2023. Avoided carbon emissions are treated as a capital service that wind provides.[3]

Section 1 describes the measurement issues related to externalities and shadow values, and reviews existing approaches to the valuation of wind as a renewable energy asset. Section 2 sets out the proposed methodology and data sources. Section 3 presents the shadow asset value estimates of wind. Section 4 provides a discussion of the results and of the methodological limitations to the estimation strategy. Section 5 concludes.

Section 1: Externalities and shadow values

This section reviews existing methods for wind valuation in national accounting contexts. It then integrates externalities to set out the conceptual framing for our estimation strategy in Section 2.

Section 1.1: Externalities and shadow values

The concept of externalities arose from Pigou's (1920) distinction between *private* marginal costs and benefits and *social* marginal costs and benefits. An externality, generally defined as an unintended (positive or negative) impact of an action on a third, uninvolved party, is an action for which the undertaking party neither bears the full cost nor receives the full benefit. In accounting contexts, an externality occurs when a production activity by one producer affects the exchange price of the production activity of a different producer or consumer, without a corresponding transaction taking place (Taylor et al, 2024).

With no externalities and under perfect competition, an economy's resources would be allocated efficiently. In such conditions, goods and services would be exchanged at prices which reflect all social costs and benefits. When externalities are present, resources can still be efficiently allocated if all associated social costs and benefits are fully internalised, for example through Pigouvian taxes.

[3] Avoided carbon emissions are understood as those emissions which would have been hypothetically generated in energy production, should alternative non-renewable energy sources have been used.

Should all marginal costs and benefits be internalised, market outcomes would coincide with socially optimal outcomes. However, in reality, lacking perfect conditions, market equivalent prices reflect only marginal private costs and benefits. There will be a 'welfare wedge' between what is accounted for and the value in terms of social welfare.

Many 'missing' capitals and their associated capital services are missing from national accounts precisely because they are not exchanged on the market. This is the case for many natural capital goods and services. The divergence between private and social marginal value can be large (Dasgupta, 2021).

Estimates of shadow prices can internalise the value of associated externalities or estimate a value for capital goods and services with no exchange value (Coyle and Wdowin, 2025; Dasgupta, 2021). Note that should a capital good or service have no exchange value, the shadow price estimate is based solely on the value of the externalities.

The importance of how to measure and *account* for externalities in the context of national accounts was recognised in the recently updated SNA25 guidelines. These included two new chapters dealing with measuring well-being (Chapter 34) and measuring the sustainability of well-being (Chapter 35). The SNA2025 also points towards the need for better measurement of missing capitals to make advances in *inclusive* wealth accounting. ONS has previously set out one approach to this, which reallocates economic value across different capital types (Taylor et al, 2024). In our prior work we proposed going one step further by considering approaches to estimating shadow values incorporating the additional economic value due to externalities.

Section 1.2: Wind as an economic asset

As noted previously, recent SNA25 revisions included renewable energy resources within the SNA asset boundary. As distinct economic assets requiring valuation, these are classified separately from complementary machinery, for example, wind turbines or solar panels, which are produced capital assets. Natural resources, including renewable energy resources, have previously been accounted by ONS in the thematic Natural Capital Accounts (based on the SEEA-CF framework), outside the core national accounts.[4]

As a growing sector of electricity production, renewable energy is too large to be omitted from national balance sheets (Smith et al, 2023). What is more, excluding renewable energy resources from countries' balance sheets, whilst other non-renewable energy sources are included, likely leads to an mis-estimation of a country's available energy resources (Statistics Netherlands, 2010).

Wind has an increasing share in the electricity generation mix. Wind energy (both onshore and offshore) is the largest renewable energy source in the UK as of 2024, and indeed is the largest single source of electricity in the UK, accounting for around 30% of total electricity generated. Wind energy also provides between 7-10% of global supply, and the capacity for wind energy worldwide is growing. There are numerous reasons, including economic and geopolitical, for which renewable energy provision, including wind energy, may be considered a critical infrastructure.

Yet even though wind is now explicitly recognised as a distinct renewable energy asset in SNA25, not all or any flows of wind are treated as an economic asset. The renewable energy assets that now constitute an extension to the national accounts' asset boundary relate to renewable energy resources which are "viable for use in economic production under prevailing technological and

[4] The valuation of natural capital assets in SEEA is based on the concept of exchange value.

economic conditions," (Smith, Ilas and Peszko, 2021). Where wind is valued in national accounts (natural capital satellite accounts), the market price of electricity generated is used.

The core shift in wind (and other renewable energy resource) valuation between SNA08 and SNA25 relates to where it sits in national accounts. Under SNA08, wind was not explicitly recognised as an asset and value from wind power was embedded in produced assets or implicitly captured in land values. As such, there was no separate asset category for wind. Included within the asset boundary as produced capital assets were the wind turbines (as continues to be the case under SNA25); energy generated from wind was considered a productive activity. Now, the value attributed to the natural capital asset can be distinguished from the produced capital asset. Part of the value that used to be captured in returns to produced capital can now be recorded as resource rent to the wind asset. Under the SEEA-CF, wind is not measured in terms of a stock (an environmental asset), but wind energy flows, based on electricity generation, are recorded in physical flow accounts. Similarly within this framework, however, the value of wind is considered to be captured in the value of the associated land on which the turbines sit. For offshore wind, this meant value could only be captured through produced capital assets or in physical flows of energy as a productive activity.

The UK Natural Capital Accounts, based on the SEEA framework, recognise and value wind in renewable energy provisioning services (an ecosystem service). A physical flow of renewable electricity generation is measured, and monetary values are estimated using residual value approaches. That is, capital services are valued by estimating the resource rents, the surplus economic value that remains from total revenue once production and all other costs are subtracted.

Following the most recent SNA25 guidelines, where wind is treated as a renewable energy asset, the value of wind capital services, captured by resource rents, will now be recorded under the newly classified asset category.[5]

The main conceptual obstacles to wind valuation in SNA2008 and SEEA-CF were the absence of the two necessary criteria defining an economic asset, namely, identifying ownership of the asset, and the asset bringing economic benefits to its owner (Statistics Netherlands, 2010). Furthermore, in this framework it is considered that, given its infinitely renewable nature, no stock of wind (or any renewable energy resource) can be accumulated.

On this point, a conceptual re-framing in the SNA25 allows for the valuation of a 'stock' of wind. In previous frameworks, as noted, there have been conceptual objections to the notion of capturing, in physical or monetary terms, a value of the stock of wind. However, the SNA25 sets out the conditions under which the value of a stock of wind can be measured. First, it is linked to what current infrastructure is able to capture. Secondly, it is scarce due to land availability and permit restrictions. The stock can then be measured as discounted future resource rents (just as the value of produced assets can be presented as a net present value). Within this framework, the conceptual task then concerns separating the allocation of the discounted resource rent to the renewable asset from the produced capital asset.

Table 1 below sets out the key definitional and methodological features of approaches to wind valuation from existing frameworks that are aligned with national accounting purposes and relevant to our proposed estimation of shadow values. These frameworks include: the SNA25; SEEA-CF; ONS

[5] It is likely that under the SNA25 the same residual value resource rent method will be used to measure the value of wind as a natural capital asset.

Natural Capital Accounts; and World Bank Natural Capital accounts (2021). There are significant distinctions between the prior approaches.

Table 1: Summary of approaches to wind valuation

Framework	Valuation	Valuation methods	Measurement considerations
SNA2025	Explicit recognition of **renewable energy resources as economic assets**. Produced capital assets and wind assets are separately recorded on national balance sheets. Stocks in monetary units consist of **aggregated (discounted) flows of future flows of benefits.**	Estimates of wind asset value are calculated by the **NPV of future resource rents using the residual value method**. Based on exchange values.	The wind that is accounted for as an asset for energy generation must be viable in economic production under **prevailing technological and economic conditions**. A **stock** of wind can be measured, since **scarcity** of the resource arises from the installation of wind turbines requiring permission, or not all land being suitable for wind energy infrastructure. The physical stock measure represents the quantity of wind resource with economic value. The physical stock can be viewed as the quantity component underlying the monetary asset valuation (the NPV of future resource rents from the stock).
SEEA-CF (2012)	**Wind is not recognised as an environmental asset.** Renewable energy assets such as wind turbines (produced), or land (with renewable energy as a feature), are recognised as assets. The natural capital service that wind provides, energy generation, is measured and valued. Thus, **service flows** are measured but **stocks of wind are not**, since “there is no physical stock of wind that can be used up or sold” (SEEA-CF, 5.226).	The flows of generated wind energy are valued with a **resource rent residual value approach**. Based on exchange values.	Again, the measurement scope relates to the amount of energy captured **under prevailing technological and economic conditions**. The SEEA-CF does not recognise non-land-based renewable energy resources such as **offshore wind**, or the value of wind when it is associated with **land that has no economic value** e.g. a remote desert.
UK ONS Natural Capital Accounts	The UK ONS Natural Capital Accounts include wind valuation in terms of renewable electricity provisioning services. There are annual estimates of physical flows of wind energy	**Resource rents** of wind energy are calculated, based on a **residual value method.** Based on exchange values.	The annual flows and asset values are based on existing technological conditions, not potential capture. The asset lifespan is set at 100 years.

	and their monetary valuation, as well as asset value estimates.	The asset value is estimated using a **NPV approach**. The stream of services that are expected to be generated over the life of the asset are estimated. These values are then discounted back to the present accounting period.	
Market and social resource rent (Statistics Netherlands, 2010)	The framework is based on price estimates of wind energy resources. The physical stock of wind is estimated by multiplying the capital stock by the production capacity over the life span of all windmills. Stocks of wind energy increase due to investment in windmills (produced capital assets) and windmill improved energy efficiency.	Resource rents, based on income earned, are calculated for the market-based approach for the value of the renewable energy capital service (with future resource rents discounted), and reflect the return to the use of the asset, **excluding** taxes and subsidies. Social resource rents **include** taxes and subsidies in the resource rent. Based on exchange values.	The inclusion of subsidies is intended to capture reductions in externalities (although potentially internalises externalities other than avoided carbon emissions), and thereby is intended to reflect societal preferences in valuing the wind resource.
World Bank Natural Capital Accounts (CWON, 2021)	Wind is classified as a **renewable energy asset**. Specifically, the valuation of the use of wind in **generating electricity**.	Asset valuation of wind by **resource rent estimates**, based on **residual value method**. The resource rent should be calculated as the **net present value (NPV) of the future stream of rents attributable to wind** as a resource over its lifetime. Based on exchange values. The **least cost alternative approach** is also possible, but less desirable because of complexity and data intensity.	The wind that counts is only that which is currently captured **under existing technological and economic conditions.** Regarding accounting for renewable energy assets separately from related (produced) assets, there is a risk of **double counting**: for example, measuring both the increase in value of a farmer's land from installation of a wind turbine and the asset value of the associated wind energy production.
Present paper approach (Wdowin and Coyle, 2026)	The approach follows the SNA25 in considering renewable energy resources as economic assets. The 'shadow value' approach considers the **marginal social valuation** of associated externalities in estimating a broader value contribution of wind to social welfare.	Valuation of **marginal social welfare values**. Market price equivalent valuation of **associated externalities** (in this paper the monetary value of avoided carbon emissions from non-renewably generated electricity services) aggregated with the market price equivalent valuation of renewable energy provisioning services (provided by onshore wind as a resource).	Avoided carbon emissions associated with the generation of wind-powered electricity are treated as a physical stock and represent the quantity of avoided emissions with economic value. The NPV of the stock is calculated for future flows of benefits over 100 years, using carbon values and discount factors.

		A NPV approach is taken to both wind and avoided carbon emissions: estimates of (market price equivalent) wind asset value are calculated on the basis of the NPV of future resource rents using the residual value method. Next, the NPV of future avoided carbon emissions from wind energy is calculated.	

<u>Section 1.3: A shadow valuation approach to wind as a renewable energy asset</u>

The issue that remains, if wind is valued consistently with SNA25 guidelines in terms of the market equivalent value of wind-powered electricity, is the omission of the value of associated externalities. There are a range of externalities associated with wind energy. For example, wind energy avoids carbon emissions, or may produce sound or visual pollution (Ramalho et al, 2025). The exchange value of the wind energy service may thus be an undervaluation or overvaluation of its contribution to social welfare. We seek to estimate the contribution of wind to social welfare, as distinct from market price equivalent valuation (at the basis of SNA25 and SEEA accounting frameworks), as well as from the approach in Taylor et al (2024), which takes a different definition of shadow prices (see also Coyle and Wdowin, 2025).

Not all externalities fall within the SNA asset or production boundaries. Some associated externalities may be reflected in market prices, and therefore will be captured within the SNA framework. For example, property prices or land values may be impacted due to wind turbines.[6] These impacts would be recorded insofar as they are observed in market transactions. But others are externalities that do not directly influence market transactions, falling outside of the SNA asset boundary, such as visual disturbance.

The key externality associated with wind energy, however, is that it produces no carbon emissions at the point of generation, in contrast to energy produced by burning fossil fuels. The exchange value of fossil fuels overvalues their economic benefit in terms of social welfare by their failure to internalise the carbon cost. The market price equivalent value of wind does not reflect the value to social welfare of the *avoided* carbon emissions[7] that wind energy provides. Should non-renewable energy prices, *including the cost of carbon emissions*, be compared against wind energy prices, a different picture of relative value would emerge. Accordingly, we treat avoided carbon emissions as a valuable capital service that wind provides.

The inclusion of avoided costs (or avoided physical flows) is not a technique typically employed in national accounting valuation methodologies.[8] In keeping with this, nor are avoided physical flows or costs of carbon emissions recorded in SNA or SEEA-based accounts.[9] Carbon sequestration is a

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[6] These are arguably externalities linked to the produced capital asset, which would require separate shadow valuation and value allocation across asset classifications. They are likely to be much smaller than the carbon externality.

[7] Or similarly, value of avoided carbon permits etc.

[8] Although there are some examples in terms of defensive or preventative expenditure for example on healthcare spending (Weale, 2025).

[9] However, the UK Green Book does include estimates of avoided costs, such as avoided healthcare costs from preventative actions or avoided flood damage costs for assessing infrastructure projects, that can be used in

similar ecosystem service, identified in the SEEA framework or UK Natural Capital Accounts, but it captures physical carbon emissions captures rather than avoidance. Whilst wind energy does not offer a physical carbon sequestration service in the way that wetlands, forests and oceans do, we conceptualise it as providing an environmental service of avoiding carbon emissions. In Section 2.1, we outline our treatment of avoided carbon emissions along similar methodological lines to carbon sequestration as an ecosystem service accounted for in UK ONS Natural Capital Accounts and based on SEEA guidelines.

<u>Section 2: Estimation strategy</u>

The principal question in estimating the monetary value of avoided carbon emissions hinges on the choice of how to value the carbon price. There are three main options currently used for accounting purposes: an abatement cost of carbon; a social cost of carbon; or a social resource rent valuation approach. Carbon prices recommended by the UK Green Book were previously based on the social cost of carbon, but are now currently based on estimated abatement costs. The social resource rent approach to wind valuation, developed by Statistics Netherlands (2010) and set out in Table 1, includes estimates of wind energy subsidies in resource rent calculations, which are taken to implicitly reflect the value of any negative externalities associated with wind energy. One limitation of this approach is the assumption that the only market failure that the government is seeking to correct is the carbon emissions, however subsidies could also be aimed at correcting for other positive externalities linked to wind energy, or negative externalities linked to fossil fuel-sourced energy.

In measuring the value of avoided carbon emissions, we take the estimated quantity of avoided carbon emissions from the counterfactual non-renewably sourced energy mix alternative to wind, and estimate its monetary value based on UK abatement-based carbon prices, provided by the Department for Energy Security and Net Zero (DESNZ).

We apply it to estimate the annual shadow asset value of onshore wind in the UK between 2009-2023, taking into account avoided carbon emissions. The existing approaches to valuing wind developed in the SEEA and UK Natural Capital Accounts are based on valuing renewable electricity generation (including from wind) in terms of market price equivalent values. Here, we are concerned with the *shadow* asset valuation of wind, which captures the value of an associated externality: avoided carbon emissions. Note that the value estimated reflects the social value of wind used in energy production (and is distinct from the value of wind turbines and any associated externalities of this produced asset). Furthermore, we estimate the shadow value of captured wind in energy generation, not *potential* captured wind.

As mentioned in Section 1.3, avoided carbon emissions are treated as an environmental service that wind provides. We therefore seek to estimate a monetary value for the economic benefit of this natural capital service. We assume that omitting its presence produces an undervaluation of wind as an economic asset.

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counterfactual comparisons or included as benefits in cost-benefit analyses. Avoided costs estimates are therefore currently used by policy-makers as a valued tool for decision making.

Note that we limit the shadow asset valuation exercise to one externality.[10] We take a national approach to valuing wind, due to feasibility and disaggregated data limitations.[11] Whilst physical flows and reductions[12] of carbon emissions are recorded in SEEA-based accounts, avoided carbon emissions are not recorded.

Section 2.1: Methodology

The annual shadow asset value of onshore wind in the UK is calculated as set out below in Equation 2.1.

$$v_{w,t}^{SH} = v_{w,t}^{m} + v_{c,t}^{SH} \qquad Equation\ 2.1$$

where,

$v_{w,t}^{SH}$ = shadow asset value of wind in year t.

$v_{w,t}^{m}$ = market price equivalent asset value of wind in year t.

$v_{c,t}^{SH}$ = avoided carbon emissions asset value in year t.

The annual shadow asset value of wind is estimated as the sum of (1) an annual estimate of wind's asset value (in terms of market price equivalent) and (2) the annual shadow asset value estimate of avoided carbon emissions. Essentially, this is a summation of the value of stocks of two natural capital services.

For the first component, we draw on available ONS data, and set out the methodology used for the calculations. The ONS methodology for asset valuation of renewable electricity provisioning services is based on SEEA guidelines. This methodology involves three steps, which start with annual monetary estimates of renewables provisioning service flows, including onshore wind, estimated using a residual value resource rent approach.

The residual value method for asset valuation consists in:

(1) estimation of the resource rent accruing to the wind asset in given year;[13]

(2) identifying the expected pattern of future rents over the asset's lifetime;[14]

[10] However, with suitable data, estimations can be extended to the internalising of further externalities, such as improved public health, or visual pollution. For example, Atkinson and Obst (2017) point out that the relationship between services linked to environmental assets and human health and the subsequent impact on health costs, needs to be further considered in an extended accounting context.
[11] However, one issue related to incorporating the value of externalities relates to the issue of local versus broader social welfare impacts of wind energy. Whilst a number of wider-scale positive externalities are associated with wind energy, usually relating to the environment, such as avoided CO_2 emissions which reduce air pollution and mitigate climate change or health problems (Adeyeye et al, 2020), negative externalities tend to be local, such as visual and noise disturbance (Frondel et al, 2019), or air pollution could be experienced disproportionately in certain areas. Thus, the weight of negative impacts, and overall benefits, of wind energy is not necessarily evenly distributed across society (Droes and Koster, 2021). Welfare gains and losses across society are not necessarily evenly distributed.
[12] Reductions are recorded as negative flows, for example, switches to low carbon energy sources are recorded as negative flows of carbon emissions.
[13] Unit resource rents need to be smoothed to address price volatility that arises from intermittency, variability of wind energy prices at different hours, seasons, and depending on demand.
[14] Based on SEEA, it is assumed that future rents will be equal to rent observed in the year of most rent available data.

(3) calculating the asset value as the sum of the discounted present value of the expected future stream of rents from wind.

Regarding step (1), employing the resource rent method in the context of the UK Natural Capital Accounts consists in calculating annual service flows using a physical output measure of onshore wind generation from data on electricity power generation, and using UK business turnover data to value the physical output. ONS starts by calculating resource rent for the whole electricity sector, and then apportioning this to disaggregated renewable energy sources based on the proportion of electricity generated by each source.[15]

For step (2), since the lifetime of wind is understood to be infinite, the accounting horizon is set at 100 years.[16]

In step (3), the formula for wind asset valuation in Equation 2.2 is applied:

$$v_{w,t}^{m} = \sum_{t=1}^{T=100} \frac{RR_t}{(1+r)^t} \qquad \textit{Equation } 2.2$$

where,

$T = 100$ is the wind asset lifetime.

RR_t = resource rent in year t.[17]

r = discount rate.

$(1+r)^t$ = discount factor in year t.[18]

A calculation of the shadow value of a stock of avoided carbon emissions in monetary terms is needed for the second term in Equation 2.1.

For consistency with ONS natural capital accounting methods, we draw on the methodology of the SEEA approach to valuing carbon sequestration services in order to estimate the shadow value of avoided carbon emissions.

Our approach involves six steps to calculate the NPV of future avoided carbon emissions over the 100-year lifetime horizon. We use projected annual gross avoided carbon emissions, valued using UK carbon values[19], and discounted. The formula is presented in Equation 2.3.

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[15] Financial accounts data on profits and costs of renewable electricity generation for the renewable energy companies is unavailable for a direct resource rent estimate of wind (renewable) energy. Data on profits and costs from other electricity generation is, on the other hand, available.

[16] This is consistent with the SEEA and UK Natural Capital Accounts approach to renewable energy asset accounting lifetime horizons.

[17] The annual resource rent estimates provided by ONS are in real terms (2024£). This puts both parts of Equation 2.1 in real terms on the basis of the same price index. This aligns also with the 2024 price index used as the deflator for the carbon prices, discussed below.

[18] Discount factors are not further adjusted for inflation. This is because resource rents are already expressed in constant 2024 prices.

[19] The UK Government (DESNZ) estimates and projects carbon values based on a target consistent approach, which builds on estimates of abatement costs that would be aligned with meeting specific emissions reduction targets.

$$v_{c,t}^{SH} = \sum_{t=1}^{T=100} \frac{A_t \cdot p_t^c}{(1+r)^t} \qquad Equation\ 2.3$$

where,

A_t = avoided emissions, tonnes of CO_2, in year t.

p_t^c = price of carbon in year t.

The six steps for avoided carbon emissions asset valuation are:

(1) Estimate annual UK onshore wind energy flows in GWh for each year.

(2) Estimate the annual physical quantity of avoided (gross) carbon emissions in tonnes, based on tonnes of CO_2 per GWh supplied by non-renewable fuel sources. This is quantities in Step 1 multiplied by estimated carbon emissions from electricity supplied by non-renewable resources for each year.[20]

(3) Estimate the annual monetary value of avoided carbon emissions for each year, using carbon prices. This involves a calculation of Step 2 multiplied by carbon prices, which gives a value estimate of the annual monetary benefits of wind's additional service.

(4) Project the expected pattern of future avoided carbon emissions over 100 years. Following SEEA and ONS natural capital accounting methodology, projected future values are taken to be constant, based on the last available year of data.

(5) Discount the annual value to obtain the present values.

(6) Sum the present values over the (remaining) 100 assumed asset lifetime years.

A number of alternatives for carbon prices must be considered. These include: market prices of carbon based on ETS allowance prices; the (global) social cost of carbon, defined variably; or country (UK)-specific policy appraisal (marginal abatement cost-based) prices. It also needs to be considered that carbon prices, whichever of the above, may be either constant in real terms. We use prices in real terms, (2024£), using a UK GDP deflator index. In summary, the three equations give the formula for the shadow asset valuation of wind expressed by Equation 2.4:

$$v_{w,t}^{SH} = \sum_{t=1}^{T=100} \frac{RR_t + (A_t \cdot p_t^c)}{(1+r)^t} \qquad Equation\ 2.4$$

Section 2.2: Data sources

We begin with estimates of the annual asset value of wind 2009-2023, in terms of market price equivalent values, from ONS's Natural Capital Accounts (renewable electricity provisioning services,

[20] Disaggregated data on fuel sources used in electricity supply is available for coal, gas and a mix of all non-renewable energy sources (DUKES 5.14).

disaggregated to UK onshore wind). ONS derives these estimates using the resource rent methodology described earlier in Section 2.1.

To estimate and value avoided carbon emissions for 2009-2023, a range of data sources is used. Estimates of annual physical flows of onshore wind across the UK (electricity generated by onshore wind), recorded in GWh, are calculated from data provided by ONS and Digest of UK Energy Statistics (DUKES, Table ET 6.1) from the UK Department for Energy Security and Net Zero. The estimate of annual onshore wind energy flows generated across the UK are summed from estimates over three habitats: enclosed farmland; mountains, moorland, and heath; and semi-natural grassland.[21] Estimates of annual UK carbon emissions from electricity from all non-renewable energy sources, in terms of tonnes of CO_2 per GWh supplied, is again provided by DUKES (Table 5.14).

Non-traded carbon values per tonne of emissions (in 2022 prices) for 2009-2123 are drawn from DESNZ.[22] We use the GDP deflator to convert to 2024 equivalent prices. Constant prices of carbon using the same base year, 2024, are used for all years of shadow asset valuation. This is consistent with the ONS estimates of wind asset values, provided in 2024 prices (£). These carbon values are set to be consistent with UK-specific targets for policy appraisal involving carbon emissions, and differ from global social costs of carbon. They differ also from the market price of carbon. They are available from 2020 to 2050. For other years, we follow the recommended approach of the UK Natural Capital Accounts, namely in that prices before 2020 and after 2050 are deflated or inflated, respectively, by 1.5% annually. We use central values in the analysis. The outlined approach is consistent with the UK ONS's Natural Capital Accounts current approach to valuing renewable electricity provisioning services.

The discount rate used to calculate the NPV of the annual monetary asset value of avoided carbon emissions follows the UK Green Book guideline rates for Social Time Preference Rates. For years 0-3, a discount rate of 3.5% is used; for years 31-75, a rate of 3.0% is used, and for years 76-125, a discount rate of 2.5% is used. The estimates will be sensitive to the choice of social discount rate, as is well established in the literature; the UK Treasury is currently reviewing its standard rates.

The remaining variables used for our shadow value estimates are based on the data set out above.

Section 3: Estimates

Below we present estimates of the shadow asset value of wind, assuming a 100-year asset lifetime (aligning with the ONS approach), mid-sensitivity carbon values, and based on a counter-factual scenario of a mix of alternative non-renewable energy sources being used in electricity production. The annex includes further sets of estimates based on low and high-sensitivity ranges of carbon values, and estimates based on an alternative scenario of the carbon intensity of gas-based electricity production alone. The annex also includes the value estimates calculated for annual avoided carbon emissions in physical terms, which are held constant over 100 years for the annual asset value calculations of each year between 2009 and 2023, in Table A4. In Table 2 below, Column A provides the ONS wind value estimates; Column B provides the value estimates of the avoided carbon emissions asset; Column C is the sum of columns A and B, providing estimates of the shadow asset value of wind; Columns D and E provide the annual rate of change in asset values for avoided

[21] Only grid-connected wind generation is measured, excluding off-grid wind energy.
[22] Table 3 of the spreadsheet that accompanies DESNZ's Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal.

carbon emissions, and the total shadow asset value, respectively. Figure 1 displays the trend of the shadow asset value of wind between 2009-2023.

Table 2: Shadow asset value estimates of wind, and rates of change, 2009-2023, 2024 prices.

Year	Wind asset value (ONS estimates), £million, 2024 prices (A)	Avoided CO_2 emissions asset value, £million, 2024 prices (B)	Total shadow asset value of wind, £million, 2024 prices (C=A+B)	Annual rate of change in avoided CO_2 emissions asset value (D)	Annual rate of change in shadow asset value (E)
2009	5,994.0368	50,729.3761	56,723,412,891	-	-
2010	4,589.9300	49,021.2443	53,611,174,354	-3%	-5%
2011	4,144.5353	76,364.0046	80,508,539,885	56%	50%
2012	4,127.9249	100,244.3181	104,372,242,933	31%	30%
2013	4,370.5109	138,836.0161	143,206,527,012	38%	37%
2014	4,040.5500	145,676.9081	149,717,458,137	5%	5%
2015	5,167.9621	173,632.9498	178,800,911,963	19%	19%
2016	5,710.7231	128,481.9129	134,192,636,064	-26%	-25%
2017	7,485.5177	177,218.3975	184,703,915,207	38%	38%
2018	8,332.2406	183,581.6974	191,913,938,049	4%	4%
2019	10,502.9372	176,974.0875	187,477,024,710	24%	-2%
2020	12,246.7353	198,505.9758	210,752,711,099	-13%	12%
2021	11,885.0162	172,247.2381	184,132,254,343	12%	-13%
2022	12,319.2749	213,634.6685	225,953,943,416	-4%	23%
2023	15,350.5320	199,402.9975	214,753,529,562	-7%	-5%

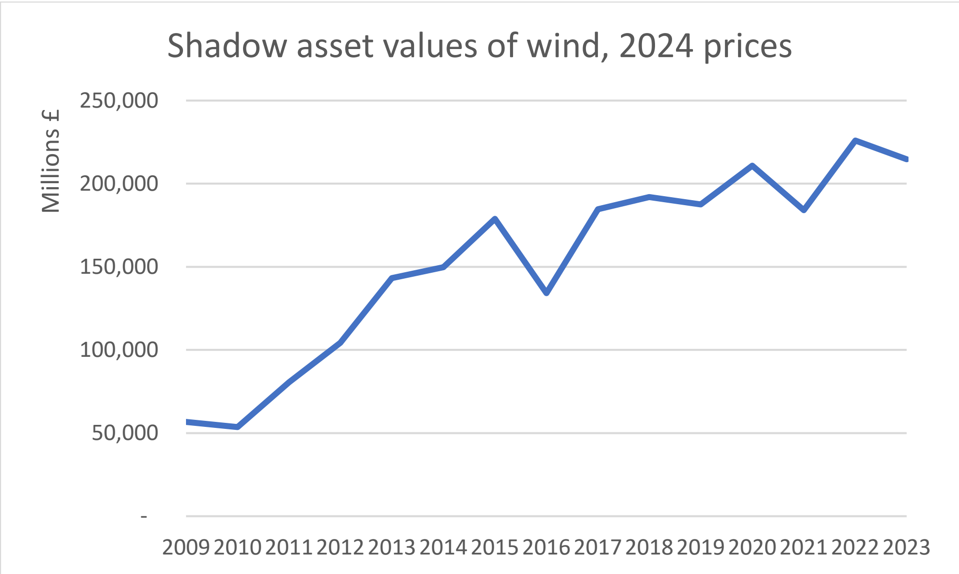

Figure 1: Shadow asset value estimates of wind, 2009-2023, mid carbon values.

Section 4.1: Discussion

Between 2009-2023, there is a variable but clearly increasing trend in the shadow asset value of wind. In some years, the shadow asset value falls sharply from the previous year, such as in 2016 and 2021. In these years, the annual wind energy generated, in GWh, falls relative to the previous year. These falls are attributed to decreases in average wind speeds in those years (GOV UK, 2016; 2022). In 2016, this drop is combined with a sharp fall in the tonnes of carbon emitted per GWh of wind energy supplied using fossil fuels, relative to the previous years, 2015 and before. The decrease in 2021 is explained by a drop in the annual wind energy generated that year. Whilst this year coincides with the covid pandemic lockdowns, the strong fall in annual wind energy generated (GWh) in 2021 from 2020 (rising strongly again in 2022) is not attributed to the pandemic but to low average wind speeds that year.

Given the much larger magnitude of the annual asset value of avoided carbon emissions, the trend tends to reflect the year-on-year changes to these annual values, rather than the trend of market-price equivalent wind asset values. In physical terms, annual avoided carbon emissions (from wind energy use), follow a slightly variable, but overall increasing trend, and carbon values follow a consistently positive trend over the entire asset lifetime horizon. The discount rate compounds heavily over a one hundred year time horizon, and reduces the present value of the future benefits, notably so over a long time horizon. Therefore, the net effect is that of declining present value of avoided carbon emissions. Before discounting, the annual estimated monetary value of avoided carbon emissions in real terms is strongly increasing year on year, one hundred years into the future. Only after discounting do the estimated annual values of avoided carbon emissions follow a declining trend over one hundred years into the future. Weitzman (2001) showed that when there is uncertainty about the long-run discount rate, a discount rate that declines over time to around zero in the far-distant future should be used (a hyperbolic discount rate). This finding is influential in the UK Green Book standard of using a declining discount rate in natural capital valuation, giving damages from far future CO_2 emissions greater weight than when constant discount rates are used. However, should a stronger hyperbolic discount rate be used (below 2.5% and converging towards zero), the estimates presented here are lower bound estimates.

The shadow asset value estimates of wind, adding the value of the annual gross avoided carbon emissions asset, are vastly larger than the market price equivalent asset value estimates provided by ONS, and dominate the total shadow asset value estimate. This may be attributed to high carbon values (the UK's appraisal carbon values are much higher than market values). Whilst the shadow value estimate of wind should be taken with caution due to methodological issues outlined below, the market price equivalent asset valuation of wind is a clear underestimate of its social welfare value.

A number of alternative scenarios are modelled, and estimates based on these alternative assumptions are included in the Annex. Whilst mid-sensitivity carbon values are used in the main analysis, the annex includes shadow asset value estimates for low (Table A1 and Figure A1) and high (Table A2 and Figure A2) sensitivity carbon values. The use of low carbon values results in an analogous rising trend in shadow asset values of wind, with the same sharper dips in value in 2016 and 2021. However, the value estimates are significantly smaller in magnitude than when mid carbon values are used. Proportionally the rise in shadow asset values is also less steep compared with mid and high values. A high carbon value assumption shows the same increasing shadow asset value trend, larger magnitude value estimates, and the most steeply increasing trend in wind shadow asset value estimates, as seen in Figure A3.

Additionally, Table A3 and Figure A4 show the shadow asset estimates based on carbon emissions from the use of gas alone as an energy source. For each year the value estimates are consistently lower than those based on avoided carbon emissions based on mixed non-renewable sources. This is because emissions are less carbon intense on the basis of gas as a source, and less carbon emissions are being avoided each year when other non-renewable sources, such as coal, are excluded from the mix. This is depicted in Figure A5 which shows the difference in shadow asset estimates when the avoided carbon emissions asset is valued based on the carbon intensity of emissions from gas energy sources or a mix of non-renewable energy sources.

Whilst in physical terms, avoided carbon emissions generally follow a rising trend in absolute terms, albeit with slowing increases, it can be expected that as countries such as the UK tend towards net-zero economies, or reduced CO_2 emissions, and as wind energy shares of electricity increase, there are diminishing marginal gains in avoided carbon emissions as the grid decarbonises. That is, the absolute cumulative avoided emissions in physical terms will be increasing at a falling rate, and marginal gains in total avoided carbon emissions will be decreasing.

This may not be the case should energy demand increase strongly, with a continued strong reliance on non-renewable energy sources. Subject to carbon prices, the value of the long-term stream of benefits from wind, most specifically the service of avoided emissions, will likely also see a decline, even if wind energy increases. On the other hand, as has been indicated the valuations remain highly sensitive to the choice of discount rate.

Section 4.2: Limitations and assumptions

As noted throughout the methodology set out in Section 2.1, the empirical analysis and value estimates are grounded in a number of assumptions. These mean that the estimates here should be considered with appropriate caveats in mind. We discuss these issues in this section, and highlight limitations to the estimation strategy and areas for future research.

The first methodological limitation relates to the use of projected future estimates for a number of variables. These include estimates of annual avoided carbon emissions being held constant one hundred years into the future, and carbon values (£). The methodology used in this paper is pursued for consistency with the current methodology used in the ONS Natural Capital Accounts estimation strategy.

Following the ONS Natural Capital Accounts strategy for estimating future values, a constant value of service flows recorded for a given year is held into the future over the lifetime horizon of the wind asset. This makes the assumption that viable wind energy capacity does not change over the years following the capacity assumed for the base year, and implies there is no integration of changing energy-related trajectories. Given the UK government's net zero policy, and plans to further increases in the share of electricity generated by wind power, as well as further future plans to increase wind energy production, this is a weak assumption. Forecasted values may be better predicted from an integration with data based on government plans for wind energy expansion or subsidies, with available data. Data based on such plans, however, is prone to volatility in nature, too. Similarly, given available data or information on (changing) carbon-intensity reducing technologies or abatement costs, projected intensity of carbon emissions from electricity provision may be weighted accordingly to move away from future values being estimated using current values. Regarding carbon prices, an alternative approach to average current values is the use of forward price curves, depending on available data.

Regarding carbon values, as mentioned in Section 2.2, these are UK-specific for policy appraisal aligned with UK emissions goals, and provided by DESNZ for the years 2020-2050. It is recommended that carbon values before and after these years are projected based on annual deflation or inflation, respectively, by 1.5%, of the most recent current value. Applying this approach far into the future, (up until 2123), for the 100-year accounting horizon of wind, leads to increased uncertainty in projected values, and high carbon values in the future. Similarly, discount values used are those established for government policy appraisals set out in UK Green Book Social Time Preference Rates. Also based on future scenario modelling (IPCC, 2023), these rates are prone to the same issues of uncertainty and volatility as carbon values. Using UK-specific appraisal values has the drawback of being potentially unreflective of global trends.

Secondly, projected future values introduce a high degree of speculation and uncertainty, particularly the further into the future they reach. Given the asset lifetime of wind is taken at 100 years, the shadow asset value estimates are based on forecast values: in this case, constant values projected into the future, such that, in theory, the flow of services associated with the asset stock of wind in 2012 is the flow from the stock that existed in 2012, rather than the flow that is actually recorded and based on any changes that have occurred to the capacity for viable wind energy production. Whilst future shadow asset values of wind are not estimated,[23] projected future values are required to estimate the NPV stream of future benefits from wind. To avoid estimates with high degrees of uncertainty linked to speculative future forecasts, the results reported in this paper are limited to the years 2009-2023, in line with the ONS Natural Capital Accounts approach to renewable electricity provisioning services. With reliable data on which future projections could be based, further work would extend shadow asset valuations into future years. However, the same uncertainty issues apply as previously in using projected future value estimates.

Regarding estimation choices, the value estimates displayed in Section 3 are based on estimated displaced carbon emissions from electricity supplied by all non-renewable fuel sources. However, the volume of avoided emissions depends on what wind displaces. This choice impacts upon the assumed intensity of the carbon emissions, since carbon emissions from gas fuelled electricity are less intense than those from coal fuelled electricity. Estimates of emissions from electricity supplied by all non-renewable fuel sources lie between those estimated for gas or coal fuelled electricity alone.

The estimated shadow asset values of wind are based on gross avoided carbon emission estimates. Given available data, future valuations may look to shadow asset valuations based on net avoided carbon emissions.

Future work may seek to capture the additional value of a range of further externalities associated with wind-powered electricity generation. Data constraints for measuring further relevant non-market externalities in monetary terms pose the main obstacle. We do not attempt to internalise all externalities associated with wind in the shadow asset value estimates above.

Section 5: Conclusion

The paper puts forward a methodology for estimating the shadow asset value of wind, based on existing estimates of wind in terms of market price equivalent values. The value estimates suggest that wind asset estimates based on market price equivalent values are an underestimate of the contribution of wind energy to social welfare, when avoided carbon emissions are considered a

[23] Nor are future asset values of wind in terms of market price equivalent values provided by the UK ONS in their Natural Capital Accounts.

capitalised service. By disaggregating the valuation of the asset in terms of market price equivalent value and incorporated externality value, the shadow asset valuation methodology furthermore provides a transparent and reproducible framework that can be applied to estimate the shadow value of other (missing) capital assets within a national accounting context. While the approach offers a practical tool for extending national accounts beyond conventional metrics, the results should be interpreted with caution due to a number of methodological assumptions and issues, in part related to data availability. The analysis contributes to the Beyond GDP research agenda specific to national accounting by providing an empirical demonstration of estimating shadow values. Overall, this study also highlights the potential for integrating non-market assets into broader economic assessments.

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Annex

Table A1: Shadow asset value estimates of wind using low carbon values

Year	Wind asset value (ONS estimates), £million, 2024 prices (A)	Avoided CO_2 emissions asset value, £million, 2024 prices (B)	Total shadow asset value of wind, £million, 2024 prices (C=A+B)
2009	5,994.0368	25,364.6880	31,358.7248
2010	4,589.9300	24,510.6222	29,100.5522
2011	4,144.5353	38,182.0023	42,326.5376
2012	4,127.9249	50,122.1590	54,250.0839
2013	4,370.5109	69,414.7432	73,785.2541
2014	4,040.5500	72,831.5699	76,872.1199
2015	5,167.9621	86,804.1081	91,972.0702
2016	5,710.7231	64,228.6966	69,939.4197
2017	7,485.5177	88,587.9591	96,073.4768
2018	8,332.2406	91,764.3187	100,096.5593
2019	10,502.9372	88,457.0620	98,959.9992
2020	12,246.7353	99,214.3680	111,461.1033
2021	11,885.0162	86,085.7360	97,970.7522
2022	12,319.2749	106,764.8742	119,084.1491
2023	15,350.5320	99,647.3743	114,997.9064

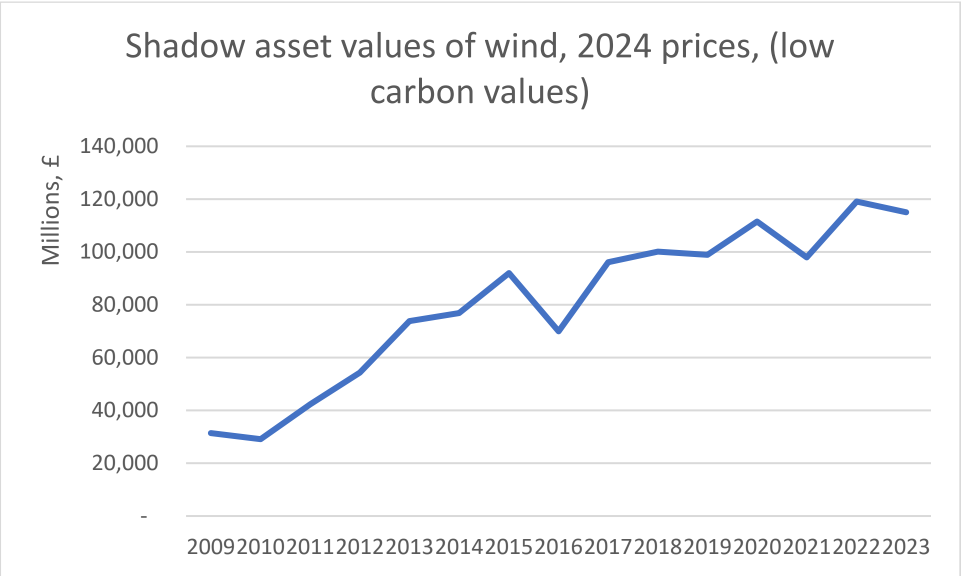

Figure A1: Shadow asset value estimates of wind, 2009-2023, low carbon values.

Table A2: Shadow asset value estimates of wind using high carbon values

Year	Wind asset value (ONS estimates), £million, 2024 prices (A)	Avoided CO_2 emissions asset value, £million, 2024 prices (B)	Total shadow asset value of wind, £million, 2024 prices (C=A+B)
2009	5,994.0368	76,094.0641	82,088.1009
2010	4,589.9300	73,531.8665	78,121.7965
2011	4,144.5353	114,546.0070	118,690.5422
2012	4,127.9249	150,366.4771	154,494.4020
2013	4,370.5109	208,244.2297	212,614.7406
2014	4,040.5500	218,494.7097	222,535.2597
2015	5,167.9621	260,412.3243	265,580.2864
2016	5,710.7231	192,686.0898	198,396.8129
2017	7,485.5177	265,763.8774	273,249.3951
2018	8,332.2406	275,292.9561	283,625.1968
2019	10,502.9372	265,371.1859	275,874.1231
2020	12,246.7353	297,643.1039	309,889.8393
2021	11,885.0162	258,257.2080	270,142.2243
2022	12,319.2749	320,294.6225	332,613.8974
2023	15,350.5320	298,942.1230	314,292.6550

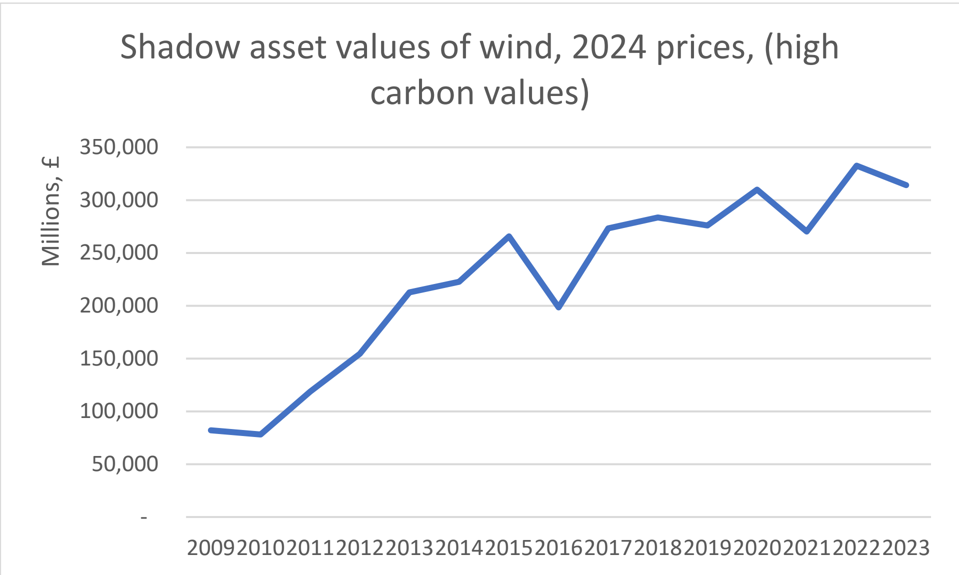

Figure A2: Shadow asset value estimates of wind, 2009-2023, high carbon values.

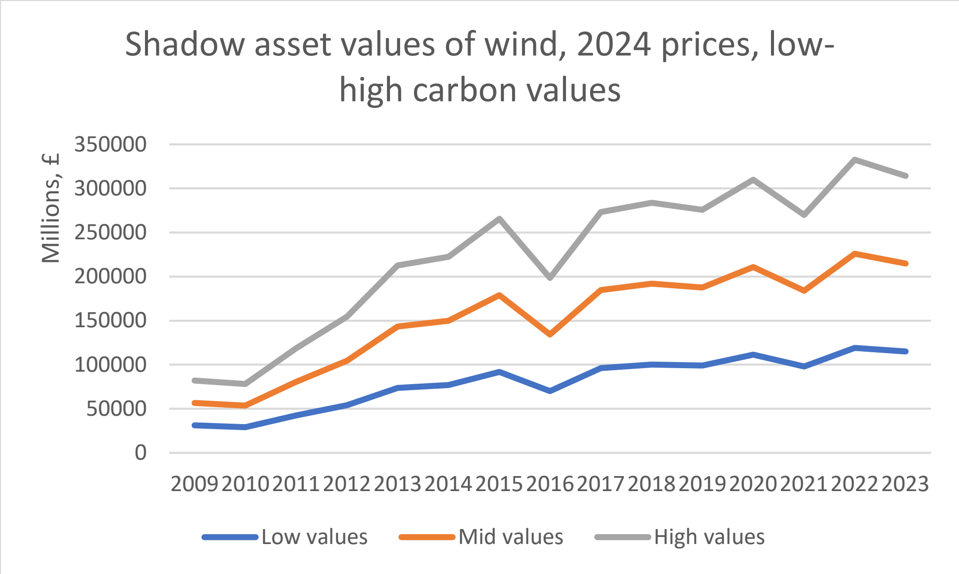

Figure A3: Comparison of shadow asset value estimates of wind, 2009-2023, low-high carbon values.

Table A3: Shadow asset value estimates of wind based on intensity of carbon emissions from gas use only, mid carbon values

Year	Wind asset value (ONS estimates), £million, 2024 prices (A)	Avoided CO_2 emissions asset value, £million, 2024 prices (B)	Total shadow asset value of wind, £million, 2024 prices (C=A+B)
2009	5,994.0368	33,762.7444	39,756.7812
2010	4,589.9300	32,570.0471	37,159.9771
2011	4,144.5353	48,090.3897	52,234.9249
2012	4,127.9249	56,142.6210	60,270.5458
2013	4,370.5109	77,968.0266	82,338.5375
2014	4,040.5500	87,451.4565	91,492.0065
2015	5,167.9621	108,201.9361	113,369.8982
2016	5,710.7231	98,711.7136	104,422.4367
2017	7,485.5177	139,426.4825	146,912.0002
2018	8,332.2406	148,913.9091	157,246.1497
2019	10,502.9372	153,908.7444	164,411.6816
2020	12,246.7353	172,877.2700	185,124.0053
2021	11,885.0162	149,572.6594	161,457.6757
2022	12,319.2749	183,184.4782	195,503.7531
2023	15,350.5320	168,970.1938	184,320.7258

Mid carbon values used.

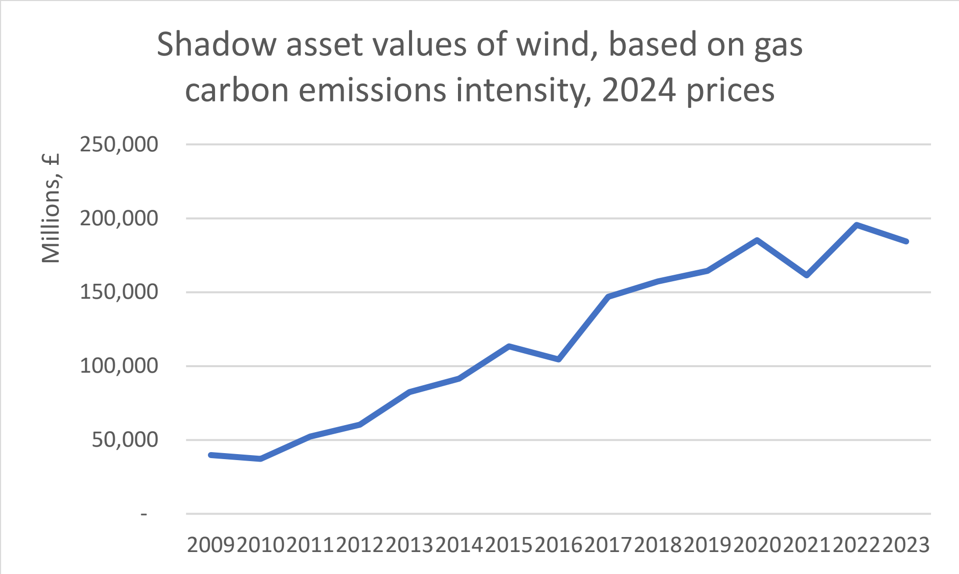

Figure A4: Shadow asset value estimates of wind, 2009-2023, mid carbon values; £millions, 2024 prices, based on intensity of carbon emissions from gas as non-renewable fuel source.

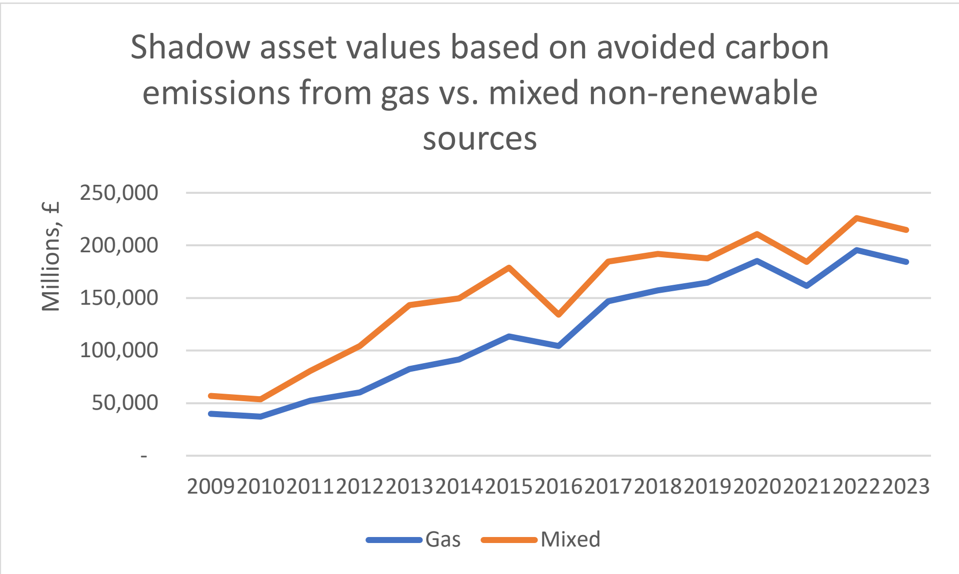

Figure A5: Comparison of shadow asset value estimates of wind, 2009-2023, mid carbon values, when avoided carbon emissions asset based on carbon emissions from gas source vs. mixed non-renewables sources.

Table A4: Avoided carbon emissions in physical terms.

Year	Annual avoided carbon emissions from wind energy generated, UK, (tonnes)
2009	4478565
2010	4263340
2011	6542470
2012	8460604
2013	11542850
2014	11930865
2015	14008276
2016	10210968
2017	13874175
2018	14158012
2019	13444920
2020	14855898
2021	12698591
2022	15515084
2023	14265744