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Abstract

The UK economy faces two immediate and enduring challenges: anaemic productivity growth since the 2007-09 financial crisis, and the increasingly urgent threat of climate change and the associated transition to Net Zero. Though their causes are independent, policy solutions to these twin challenges cannot be. Economic statistics that can simultaneously assess progress towards productivity growth and Net Zero will be needed. With this in mind, we extend economic estimates of UK productivity growth to incorporate greenhouse gas (GHG) emissions and non-GHG air pollutants. Defining productivity as the ratio of gross value-added to inputs, we explore four deviations from the standard measure. These include: incorporating the environment (emissions) as an input, examining energy-productivity, incorporating environmental protection as a 'good' output, and incorporating emissions and pollutants as 'bad' outputs. Whilst some of these themes have been explored previously, our contribution is two-fold. First, we believe we are the first to treat environmental protection expenditure as capital investment in the UK context. More fundamentally, where previous studies have adjusted *economy-wide* (i.e., aggregate) productivity measures to reflect emissions, we utilise the richness of UK data to construct *sector-specific* environmentally-adjusted productivity. We find that incorporating emissions yields higher measured output and labour productivity, but not enough to explain the productivity puzzle. Moreover, UK energy-productivity has more than doubled since 1990. Granular, industry-level data indicates that this is mostly due to increased efficiency within industries, with only 8-18% due to changing industrial composition since 1990.

Keywords: productivity, environmental accounting, national accounting, greenhouse gas emissions

JEL codes: O44, Q56, E01

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1. Introduction

The interplay between productivity growth and emissions is central to achieving economic and environmental objectives. Indeed, it may be a decisive factor in delivering economic growth and Net Zero. But the primary economic indicators (productivity and GDP growth) and the primary environmental indicators (emissions) ignore each other. Economic statistics that can simultaneously assess progress towards productivity growth and Net Zero will be needed. We contribute to this discussion by showcasing available data and methods for incorporating environmental factors into measures of economic output and productivity. We make two adjustments to measures of output. Beginning with the standard measure of gross value added (GVA), GVA-minus deducts the value of emissions and pollutants, while GVA+ adds environmental protection expenditure as a form of investment in natural capital. Subsequently, four environmentally-relevant productivity measures are presented: output per unit of emissions, output per unit of energy input, emissions-adjusted labour productivity, and environmental protection-adjusted labour productivity.

We hope to shed light on the so-called 'productivity puzzle', which refers to the protracted reduction in annual labour productivity growth from its post-War average of around 2% to about 0.7% since the 2007-09 financial crisis. Although the phenomenon holds across most developed economies, it is among the most severe in the UK.

One common explanation for the productivity puzzle is mismeasurement. If inputs, output or prices are incorrectly measured, the observed slowdown in productivity growth may merely be a statistical mirage. The standard example relates to digital output, such as free services online, or else failure to capture improvements in quality in price indices, often due to changes in digital products. Improvements to the telecommunications services deflator by ONS[2] indicate that this might partially be true. However, it can at most account for only a small part of the slowdown, given the scale of the slowdown and simultaneity across the world. It is implausible that all national accountants the world over simultaneously got substantially worse at measuring the economy.

We consider a different type of mismeasurement – the failure to account for environmental damage, and environmental protection activities. Conventional productivity measurement adopts a 'private goods' approach, assuming 'free disposal' of 'bad outputs' such as pollution. However, as externalities such as pollution and climate change become increasingly important socioeconomic concerns, the exclusion of externalities from productivity statistics becomes increasingly problematic. The Dasgupta Review demands that economics takes full account of its impacts and dependencies on nature (Dasgupta 2021). From a social planner perspective, the assumption of free disposal no longer holds and externalities (both positive and negative) need to be incorporated into productivity measurement.

There is some precedent for internalising the costs of bad outputs within productivity measurement. Shephard (1970, Ch 9, p180) extends the definition of efficiency to incorporate an explicit treatment of "nondesirable" outputs such as "waste products, which lead to pollution of air, stream and land and cost society for their control". Färe

[2] implemented in the Annual National Accounts update in 2021.

et al (1989) relax the strong disposability assumption, developing productivity indices where bad outputs cannot be costlessly deposed. Färe et al (1997) develop a directional distance function approach to model the joint production of good and bad outputs and generated a productivity index that rewards goods and penalises bads. In the environmental economics literature, environmentally-adjusted productivity measures have typically been developed in the field of agricultural economics (Repetto et al 1996; Nanere et al 2007).

Brandt et al (2014) find that deducting the value of pollutant emissions from output has only a minor effect on measured productivity, but their data restricted them to a relatively narrow set of emissions (CO_2, SO_x, and NO_x). In contrast, Statistics Canada (2019a,b) developed an environmentally-adjusted multifactor productivity (EAMFP) measure for the Canadian manufacturing sector, finding that when the value of greenhouse gas emissions is included, EAMFP between 2004-2015 grew 70% faster than the standard multifactor productivity measure, largely due to reductions in the emissions intensity of output. More recently, frameworks have been developed to incorporate SEEA-consistent natural capital data into measures of productivity growth. Brandt et al (2017) show that the sign of the adjustment to productivity growth depends on the *relative* rate of change in the use of natural capital versus other inputs. Rodriguez et al (2018a,b) decompose output growth into contributions from labour, produced capital, and natural capital, showing that output growth in OECD countries is almost entirely due to productivity growth, in BRICCS countries it is largely due to increase use of inputs.

The effect of incorporating emissions (a negative externality) on the growth of productivity is *a priori* ambiguous. If emissions are considered a type of 'bad output' then *ceteris paribus* incorporating them should reduce the level of measured output and therefore productivity at any point in time. However, for the growth what matters is the relative rates of growth of emissions and output. If the amount of the 'bad' falls faster than GDP rises, then GDP net of this bad output might be rising faster than currently measured. If, however, emissions are falling more slowly than GDP is rising, then that could reduce the rate of environmentally adjusted GDP growth.

Simultaneously, if businesses increasingly incur costs to protect the environment, but these costs generate no corresponding output, this would place downward pressure on measured productivity. If these environmental protection expenditures were instead treated as a type of capital investment (in a type of natural capital) they would add to rather than detract from GDP. If this type of expenditure were increasing faster than GDP, then capitalising it could raise the trend of economic growth and thus productivity. If it is not increasing as quickly as GDP, or not increasing at all, then adjusting for this could reduce the rate of GDP growth.

Our contributions are twofold. First, we believe we are the first to treat environmental protection expenditure as capital investment in the UK context. More fundamentally, where previous studies (OECD 2018) have adjusted *economy-wide* (i.e., aggregate) productivity measures to reflect emissions, we utilise the richness of UK data to construct *sector-specific* environmentally-adjusted productivity.

There are several paths through which climate might affect long-term productivity. Rising and increasingly volatile temperatures could reduce labour productivity (Letta and Tol 2019; Kahn et al 2021), impair physical capital[3], and lead to asset stranding. The consequences of a climate-driven reduction in long-run productivity growth could be substantial. Fankhauser and Tol (2005) showed that with a constant saving rate, climate induced reductions in output would yield a corresponding reduction in savings (equivalently, investment), reducing capital accumulation. Under endogenous technological change, they show that the capital accumulation effect may be greater than the direct physical effect of climate change. Subsequent theoretical papers showed that if climate change reduces TFP growth then the urgency and stringency of climate policy would increase substantially (Stern 2013; Moore and Diaz 2015; Dietz and Stern 2015; Moyer et al. 2014). A subsequent series of empirical estimates suggest the long-run effect of temperature change on growth is significant (Dell et al 2012, 2014; Kalhul and Wenz 2020; Kahn et al 2021). We differ from these studies in two important ways. Where they implicitly assume that productivity is appropriately measured and focus instead on its future relationship with temperature, we are principally interested in how productivity measures themselves might be adapted to incorporate emissions and natural capital investments. Second, where they focus on modelling exercises, we consider recent and current trends.

The paper is organised as follows: Section 2 introduces the conceptual framework. Sections 3-7 construct sector-specific time series of, respectively: energy productivity, emissions productivity, labour productivity with bad outputs, and labour productivity with an unmeasured good output. We also consider the sensitivity of these with respect to various assumptions, especially the choice of the 'price' of emissions. Section 8 concludes.

2. Conceptual framework

Productivity is a measure of how much output is produced per unit of input and estimates are sensitive to how output and inputs are measured. Productivity growth measures are generally calculated in volume terms – that is, ignoring prices and price changes. As such, the output and input measures should be volume terms. These are occasionally observed volumes, such as 'miles transported' in the case of transport services, but more often as calculated by adjusting a value measure for price changes over time.

The headline labour productivity measure produced by the ONS is a single-factor labour productivity measure: output per hour worked[4]. Output here is gross value added (GVA), which is the value of goods and services produced after deducting intermediate goods and services used in the production process. GVA can be added across firms and sectors without double-counting, and is thus the bedrock of National Accounting and GDP. To put GVA into volume terms, a set of price indices (deflators) are used to remove price change effects over time.

[3] Long-lived infrastructure that has been optimised for past and current climatic conditions may perform poorly in the face of increasing extremes. For instance, the February 2021 winter storm in Texas crippled the State's energy infrastructure which had not been designed to operate in sub-zero temperatures. Resulting blackouts left millions without power for days, contributing to 246 deaths.
[4] Hours worked are a preferred labour input measure since they relate to the actual quantity of labour used, differentiating effectively between workers on different working contracts, for instance.

2.1 Productivity growth from a private goods perspective

Total factor productivity (TFP) is defined as the ratio of outputs Q to inputs I.

$$TFP = \frac{Q}{I} \tag{1}$$

Expressing this in growth terms, we have

$$T\dot{F}P = \dot{Q} - \dot{I} \tag{2}$$

Where $T\dot{F}P$, $\dot{Q}$, and $\dot{I}$ represent growth in total factor productivity, total output, and total inputs, respectively. Rearranging, we have:

$$\dot{Q} = T\dot{F}P + \dot{I} \tag{3}$$

Following Repetto et al (1996) and Nanere et al (2007), environmentally adjusted productivity is obtained as follows:

$$Q = A\, f[K, L] \tag{4}$$

Where Q(t) is real output in year *t*; K(t) and L(t) represent capital and labour inputs, respectively; and A(t) is a productivity index. From here, the rate of productivity change is:

$$\frac{A'(t)}{A} = \frac{Q'(t)}{Q} - \left[\frac{s_k K'(t)}{K} + \frac{s_l L'(t)}{L}\right] \tag{5}$$

Where primed quantities represent rates of change with respect to time. Put simply, the rate of productivity change is merely the difference between the rate of change in outputs and the rate of change in inputs. For completeness, s_k and s_l are output elasticities, which under *ceteris paribus* conditions represent the proportional change in output arising from a small change in the input. Under perfect competition and constant returns to scale, these elasticities represent the share of total costs attributed to each input and thus sum to one.

2.2 Productivity growth from a social welfare perspective

To incorporate environmental externalities, we define total output from the social welfare perspective, W, as the sum of market output, Q, and an environmental externality, E, with output shares denoted by s_q and s_e, respectively. Thus, production technologies that reduce say the emissions intensity of output would be captured by reductions in s_e. The growth rate of total output is then described as:

$$\frac{W'(t)}{W} = \frac{s_q Q'(t)}{Q} + \frac{s_e E'(t)}{E} \tag{6}$$

If E represents a negative externality such as pollution, its shadow price, s_e, is negative and the value of total output, W, falls as E rises.

Letting A^* denote productivity from a social welfare perspective, net of externalities and encompassing both market and non-market outputs, we can describe environmentally-adjusted productivity growth as:

$$\frac{A^{*'}(t)}{A^*} = \frac{s_q Q'(t)}{Q} + \frac{s_e E'(t)}{E} - \left[\frac{s_k K'(t)}{K} + \frac{s_l L'(t)}{L}\right] \quad (7)$$

Productivity growth from the private goods perspective (5) differs from that in the social welfare perspective (7) by an environmental-adjustment term:

$$\frac{A^{*'}(t)}{A^*} = \frac{A'(t)}{A} + s_e \left[\frac{E'(t)}{E} - \frac{Q'(t)}{Q}\right] \quad (8)$$

2.3 Environmentally-adjusted productivity measures

For this paper we will use only single-factor productivity measures, but we will alter either the input or output measure to make them more 'environmentally-relevant'. The first two measures we will consider are single-factor productivity measures, where the single-factor is not labour. We will replace labour in the denominator: first with energy use, and second with greenhouse gas emissions. The second two measures we will consider are labour productivity measures, where the output measure is modified. The first of these treats greenhouse gas emissions and air pollutants as 'bad' outputs, deducting the volume of emissions from the volume of GVA. The second treats environmental protection activity as an unmeasured good output, and is added to GVA.

Thus, we have four main environmentally-adjusted single-factor productivity measures:

- energy-productivity = $GVA\ /\ energy\ use$
- emissions-productivity = $GVA\ /\ emissions$
- labour productivity with bad outputs = $GVA\ minus\ /\ hours\ worked$
- labour productivity with unmeasured environmental investment = $GVA\ plus\ /\ hours\ worked$

3. General points on data

The main tenets when producing productivity estimates are that the measure of inputs and the measure of outputs should relate as closely as possible to the same activity. Put another way, that the measured inputs are indeed the ones used to produce the measured output.

Specifically, this requires that the data relate to the same economic units, based on the same production boundary, and over the same time period. For instance, for a labour productivity measure of the whole economy of the UK, the labour (e.g. number of workers) should relate to those people who contributed to UK GDP in the relevant time period. People not working, or working in the UK but for a business that contributes to another country's GDP, should not be included.

3.1 Environmental data

In the case of the environmental data, this means that we want them on a resident basis, which aligns with the measures of Gross Value Added (GVA) from the National Accounts that we use as our output measures. A "resident" basis means that all economic units that contribute to UK GDP are included, regardless of where they are geographically located. For instance, a manufacturing plant in France, owned by a UK company, would be included in GDP and in the resident-based energy use data. Meanwhile, a French-owned plant that is located in the UK would not be included. This contrasts with a "national" basis, which is based on the geographical territory of the UK.

A second coverage issue is the difference between a production and consumption basis. Emissions on a production basis relate to emissions created through economic production in the UK, whereas a consumption basis would attribute emissions to the UK that were produced abroad if the UK is the consumer of the relevant products. Production and consumption bases therefore differ by a measure of the net emissions of exports and imports. For many purposes, a consumption basis is preferred since it more fully reflects the emissions caused by a country. For instance, if the UK outsourced production of consumer goods to Asia, then it might see lower emissions on a "production" basis, but no change (or even an increase, depending on the relative emissions-productivity of the UK and Asia) on a "consumption" basis.

For our purposes, we are primarily interested in measures on a "production" basis, for two main reasons. First, conceptually, we need to match the inputs and outputs as closely as possible for productivity measures. Emissions produced abroad for goods that are imported to the UK may contribute to UK consumption and GDP, but are not directly in control of UK industries. Thus, when comparing emissions with GVA, or emissions-adjusted GVA with hours worked, we need only those emissions that are related to that GVA and those hours worked. We would not, for instance, include the hours worked or GVA of the imported goods. The outsourcing of manufacturing from the UK to Asia would show up as a decline in GVA, hours worked and emissions of UK manufacturing, and a structural change in the composition of the economy – all of which we will capture through the production measure. A second, practical reason to focus on the production basis is that the data are more readily available by industry and over time, than for the consumption basis.

We exclude energy use and emissions by consumers, in the course of their personal transport and heating of homes. Since household production is not in the production boundary for GDP, this is appropriate for productivity measures. Consumer energy use and emissions are a large fraction of the respective totals, however, so our measures do not account for all energy use or emissions in the UK.

We use contemporaneous measures of energy use and emissions as for output. A challenge here is that emissions may be recorded after the activity that led them to be created – in some cases, well after. For instance, emissions from a landfill site will be recorded as they are emitted, but the waste may have been created (and relate to economic activity) many years before. Ideally we might like to estimate the emissions over the duration of the waste's life and attribute them all to the year in which the waste was created. This is challenging in practice.

In a steady state, if each year a similar magnitude of waste is deposited, and the emissions in that year are due to a similar amount of waste in many previous years, then the two measures would be approximately equal. If, however, the amount of waste deposited changes over time, or the emissions from existing waste change (due for instance to improving techniques to minimise emissions from landfill sites), then the steady state is not appropriate. It is beyond the scope of this paper to control for this, but note this as an interesting area for further research.

3.2 Gross value added

Gross value added (GVA) data comes from the GDP output approach low-level aggregates dataset from ONS. We use data in current prices (CP) and chained volume measures (CVMs). We construct our own CVM series for some bespoke industry aggregations – see section 3.4 for more.

We exclude imputed rental from our estimates for the real estate industry, and from GDP. Imputed rental is included in national accounts to ensure comparability across countries with different home ownership rates. While important for this purpose, it obscures productivity analysis since it appears as an output without corresponding inputs. ONS productivity datasets provide GVA estimates for the real estate industry (section L) and the whole economy excluding imputed rental, and we use these throughout.

The data are consistent with Blue Book 2021 (released on 30 September 2021) which was the first UK National Accounts to use double deflation (accounting for price changes of the inputs and output of each industry separately).

3.3 Hours worked

Data on hours worked comes from the ONS productivity statistics, as published in the "output per hour worked" dataset. These are constructed by multiplying estimates of average hours worked per job (separately for employees and the self-employed, and for first and second jobs), by estimates of the number jobs (based on business surveys and other sources). These differ from estimates from the Labour Force Survey (LFS) directly, since the industry allocation of workers differs between the LFS and the business surveys. At the whole economy level, the industry estimates are benchmarked to total hours worked from the LFS.

Given the complex nature of the estimation process, hours worked estimates are only available down to an industry-division level (and in some cases only the industry-section). As such, we must use a slightly less detailed industry in the adjusted labour productivity measures. The main loss of detail is in the agricultural, energy and land transport industries.

3.4 Industry aggregation

We aim to strike a balance between detail and reliability in the industry breakdown, constrained by data availability. In the case of the emissions and energy-productivity measures, the constraint is usually the GVA data. For the environmentally-adjusted labour productivity measures, the constraint is usually the hours worked data.

Industries are defined according to the Standard Industrial Classification (SIC) 2007 – the main industry classification used in official statistics in the UK. It is a hierarchical system, the top layer of which are 21 industry sections (denoted by letters from A to U), followed by 88 industry divisions (denoted by numbers from 01 to 99). SIC 2007 is consistent with the European industry classification system, NACE, down to 4-digits (classes), which in turn is consistent with the international standard, ISIC, down to 2-digits (divisions).

Energy use, emissions and environmental-protection expenditure are generally highest in the agriculture, mining, manufacturing, energy, utilities and transport industries. As a result, we aim for additional detail in these industry-sections, described below.

We separate agriculture (01) from forestry (02) and fishing (03), the latter two of which are relatively small industries. The GVA is no more detailed than this. Hours worked is no more detailed than section A.

For mining and quarrying, we separate oil and gas extraction (06) from the remainder of the industry-section (B). The remainder encompasses mining for solid materials, and mining services. The GVA is no more detailed than this, and we construct a bespoke CVM series for the aggregate of industry-divisions 05, 07, 08 and 09.

In manufacturing we use the sub-sections, which group together industry-divisions into related groups: for instance, manufacturing of food, beverages and tobacco are combined as industry sub-section CA. There are 13 such industry sub-sections. While the data would allow more detail, we felt this was a reasonable balance of granularity and reliability.

We would like more detail in the energy industry (section D, equivalently division 35) for obvious reasons, but the GVA data will support only a breakdown between electricity (35.1) and other energy such as gas (35.2-3). Hours worked is no more detailed than section D (equivalently division 35).

In the water and waste industry-section (E), we separate water supply (36) from the various waste services industries including sewerage and solid waste management (37-39). There are classification challenges here, and division 39 is very small, so we felt this was as detailed as feasible in this industry. Hours worked is no more detailed than section E.

In the transport industry, as the largest user of energy, we use as much breakdown as the data will support. This allows us to separate land transport by rail (49.1-2), land transport via other means including roads and pipelines (49.3-5), water transport (50), air transport (51), warehouse and storage services (52) and postal and courier services (53). Hours worked allows a breakdown by industry-division, which means aggregating all of land transport (49).

For all other industries, including construction, consumer services and business services, we use the industry-section breakdown. This gives a total of 42 industries for energy and emissions-productivity estimates, and 36 for environmentally-adjusted labour productivity estimates.

4. Energy-productivity

Energy, like labour, is a factor of production used widely across the economy, although to different degrees in different industries. However, the distribution of energy use is far more skewed than labour: labour is a ubiquitous input in all industries, and makes up a large fraction of input costs in all industries; meanwhile energy is very important in some industries, and much less important in others. Nonetheless, a measure of energy-productivity (GVA divided by energy use) is a valid single-factor productivity measure, and is of especial interest in the production industries of the economy. Energy use is in volume terms.

4.1 Data and methods

Data on energy use by industry comes from ONS tables, which are sourced from Ricardo Energy and Environment. Various tables provide different breakdowns, including by fuel type, activity, and industry. From a productivity perspective, the source of the energy (fossil fuels or renewable sources) is of little interest, so we use the data on energy from all sources. As outlined in section 3.1, the data are on a resident basis, and we exclude consumer expenditure.

Data are either on a “direct” basis, or “reallocated”, where the latter reallocates losses in the distribution and transmission system from the energy industry that produce the energy, to the ultimate consumers. The “reallocated” basis is suitable when thinking about energy demand, since arguably the energy industry only produce energy to serve customers that demand it. As such, energy lost *en route* from producer to consumer is only a by-product of the demand of the consumers.

However, the ‘using’ industry does not use the energy lost *en route*, and for productivity measure we want actual use and actual output to match up. So we use the “direct” measures, which attributes the losses in the system to the energy industry itself. Since the energy industry is most ‘in control’ of these losses, and their output is closely related to the volume of energy produced, this also makes sense for productivity measures.

Energy use is in volume terms, namely Terajoules of energy use from all sources. The energy-productivity measures therefore represent the volume of economic output (GVA in volume terms) that can be produced per Terajoule of energy used, irrespective of the price or source of that energy.

For the decomposition of aggregate productivity growth into between-industry and within-industry effects, we use a simple between/within decomposition. The within-industry contribution is growth in energy-productivity in each industry between year t

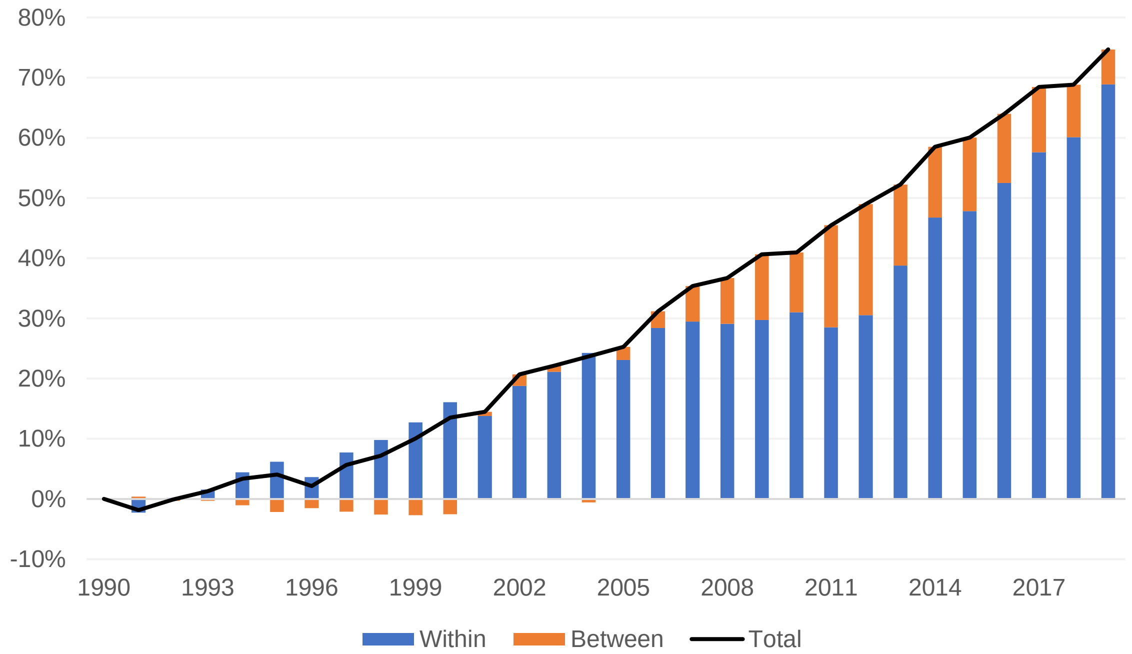
and $t-1$, multiplied by its share of energy use in year $t-1$. The between-industry contribution is the change in aggregate energy-productivity less the contributions from within-industry changes. We do all of these calculations in natural logs to ensure additivity, since using percentage changes would not be additive and thus attribute too much of the growth to the between-industry effect. However, our headline measures are in percentages for ease of interpretation. For the decomposition we use three different industry-aggregations, since different aggregations can give different results. The most detailed uses 42 industries (our bespoke aggregation, see section 3.4), the next uses 20 industries (industry-sections), and the least detailed uses just 6 industries (high-level groupings).

4.2 Results

For the whole economy, we estimate energy-productivity grew at an average rate of 2.6% per year between 1990 and 2020. In total over that period, that constitutes more than a doubling of energy-productivity. This is largely driven by increasing real GDP while energy use fell somewhat. Energy use increased modestly between 1990 and 2006, before falling about 20% between 2006 and 2020. However, relatively flat energy use in the context of rising real GDP constitutes increases in energy-productivity.

Most of the gains in aggregate energy-productivity since 1990 have come from within-industry growth. Figure 1 shows a decomposition of aggregate energy-productivity growth into within-industry and between-industry contributions. There is very little between-industry contribution before 2006, although it increases thereafter.

Figure 1 – Within/between decomposition of whole economy energy-productivity growth, 1990 to 2019



Notes: In log points rather than percentages, for additivity. It's 111% increase between 1990 and 2019, which is 75% in log points. Uses Aggregation 1 in Table.

Table 1 summarises the within-industry and between-industry contributions to aggregate energy-productivity growth for three industry-aggregations. While the results vary somewhat between aggregations, the within-industry contribution is dominant in each case. However, the within-industry contribution is consistently positive and not trivial. By contrast, the within-industry contribution to labour productivity growth in the UK over the same time period has been negative (if excluding imputed rental).

Table 1 – Summary of within-industry and between-industry contributions to aggregate UK energy-productivity growth 1990-2019, three industry aggregations

	Aggregation 1	**Aggregation 2**	**Aggregation 3**
Within			
Log points	68	61	66
% of total	90.6	82.1	89.0
Between			
Log points	7	13	8
% of total	9.4	17.9	11.0

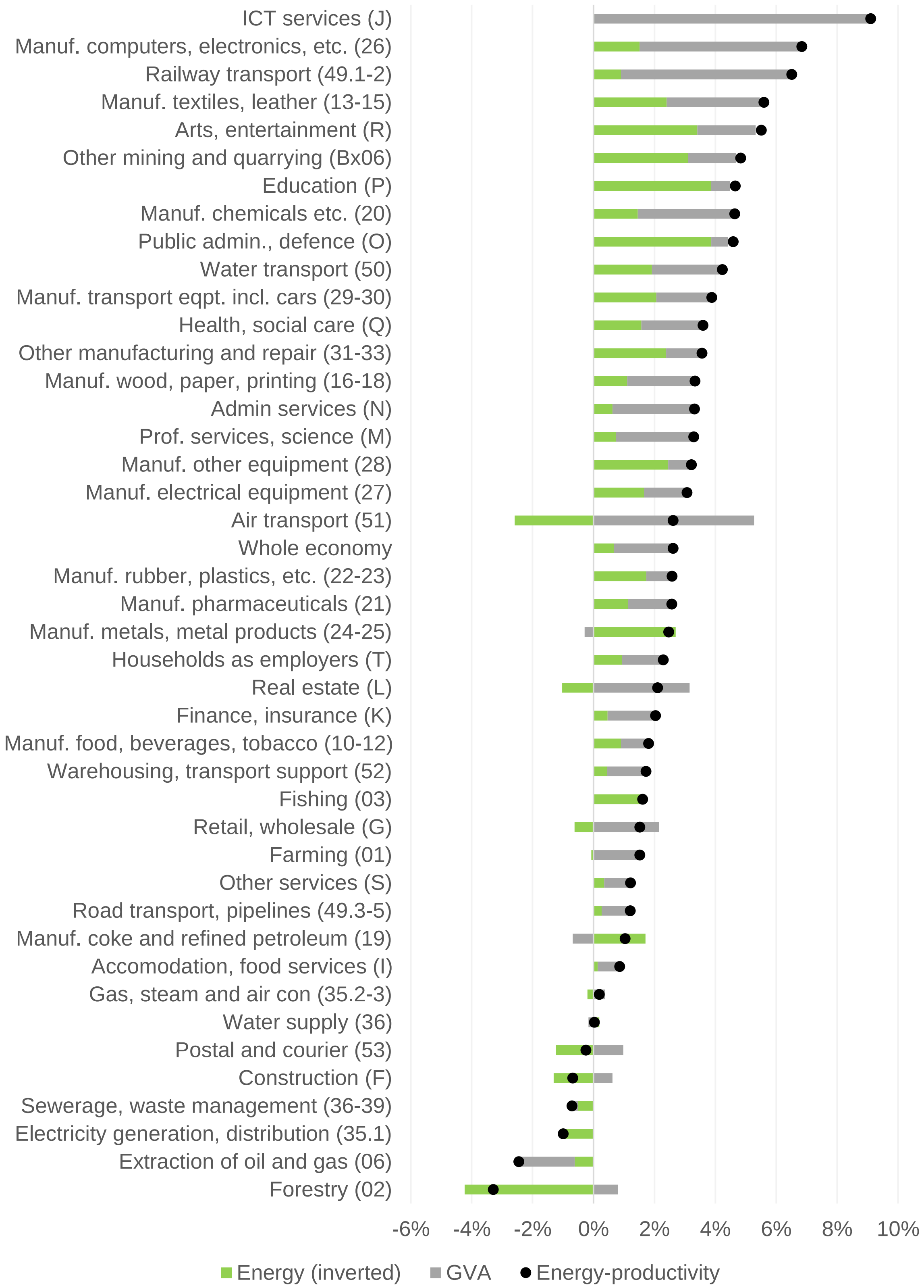
Notes: In log points rather than percentages, for additivity. Aggregation 1 is most detailed (42), Aggregation 2 is section-level (20), Aggregation 3 is least detailed (6). See section 4.1 for details.

Most industries saw energy-productivity growth between 1990 and 2019, but there is substantial variation across industries in the degree of that growth, as Figure 2 shows. The industries with the fastest increases are the ICT services industry [section J] (on account of its very rapid real GVA growth), manufacturing of xx [sub-section CI], transport by rail [industry 49.1-2], manufacturing of fabrics, leather, etc. [sub-section CB], and arts and entertainment [section R]. Most services industries see increases on account of relatively flat energy use and growing GVA. Time series charts of energy-productivity for all industries are shown in Annex B.

By contrast, a handful of industries have seen energy-productivity regress over the period, namely forestry [division 02], extraction of oil [division 06], electricity generation and transmission [industry 35.1], sewerage and waste management [divisions 37-39], construction [section F], and postal and courier services [division 53]. That majority of industries have reduced energy use between 1990 and 2019. Of those that have not, many have seen energy-productivity regress. Others include air transport [division 51], real estate [section L], retail and wholesale [section G], water supply [division 35], and farming [division 01].

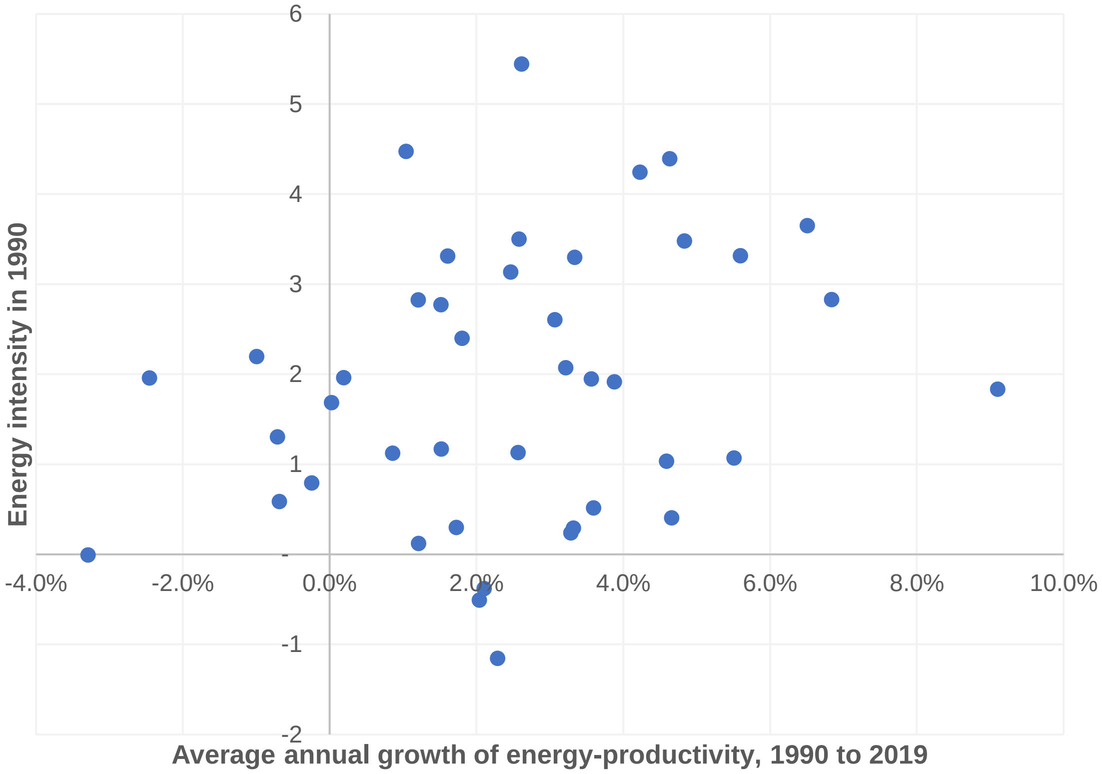
One might expect the industries using energy most intensively would be most incentivised to reduce their energy use in order to reduce their costs. However, Figure 3 shows no real relationship between energy intensity (the inverse of energy-productivity) in 1990 and subsequent energy-productivity gains.

Figure 2 – Average annual growth in energy use (inverted), real GVA, and energy-productivity, by industry, 1990 to 2019



Notes: energy use growth is inverted, since it is the denominator in energy-productivity, and thus increases in energy use reduce productivity (and vice versa). Thus, the sum of the bars is equal to energy-productivity growth. All growth rates shown are compound annual averages, in percentages.

Figure 3 – Scatterplot of average annual growth of energy-productivity between 1990 and 2019, against energy intensity in 1990, by industry



Notes: Energy intensity is $1/energy\ productivity$*, that is* $energy\ use/GVA$*. Energy intensity is in natural logs, since it varies very substantially. Growth rates of energy-productivity are compound annual averages.*

5. Emissions-productivity

Emissions-productivity (GVA divided by greenhouse gas emissions) is an extension of energy-productivity, since emissions result usually from energy use. However, changes over time in the 'green-ness' of the energy being used mean emissions-productivity can deviate from energy-productivity. We have intrinsic interest in emissions, while we are generally only interested in energy use to the extent that it implies something about emissions. Emissions-productivity measures are therefore perhaps a more useful measures than energy-productivity. That said, it is energy that is used in the production process, while emissions are the result of the production process.

5.1 Data and methods

Data on greenhouse gas emissions by industry comes from ONS tables, which are sourced from Ricardo Energy and Environment. Many of the considerations from the energy use data are the same for the atmospheric emissions data. We again use data on a resident basis, and exclude consumer activity, for the same reasons as previously. The within-between decomposition is constructed as for energy-productivity – see section 4.1.

For our emissions-productivity measures we use greenhouse gas emissions only. This covers all greenhouse gases under the Kyoto Protocol, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons (HFC), perfluorocarbons (PFC), nitrogen trifluoride (NF_3), and sulphur hexafluoride (SF_6). All are expressed in common units of tonnes of carbon dioxide equivalent. This measure is therefore broader than carbon dioxide emissions alone. In our emissions-adjusted labour productivity measures in section 6, we adjust for the economic cost of greenhouse gas emissions, acid rain precursors, and other pollutants. Since each type of emission has an associated price, we can adjust for all of them.

It would be possible to compute a composite index of emissions and pollutants, using the price per unit to establish weights. While this would give a fuller measure of emissions-productivity, we chose not to for two main reasons. First, we cannot be sure that the prices for each type of emissions are consistent, such that we might overweight or underweight each of the emission types. While this issue will also exist for our emission-adjusted labour productivity measures, there the emissions are adjustments to a total and therefore the results are less sensitive to the weighting of the emission types. Second, most other studies (e.g., the OECD green growth indicators) use greenhouse gas emissions only, so this ensures comparability between our industry measures and the national figures available from other sources.

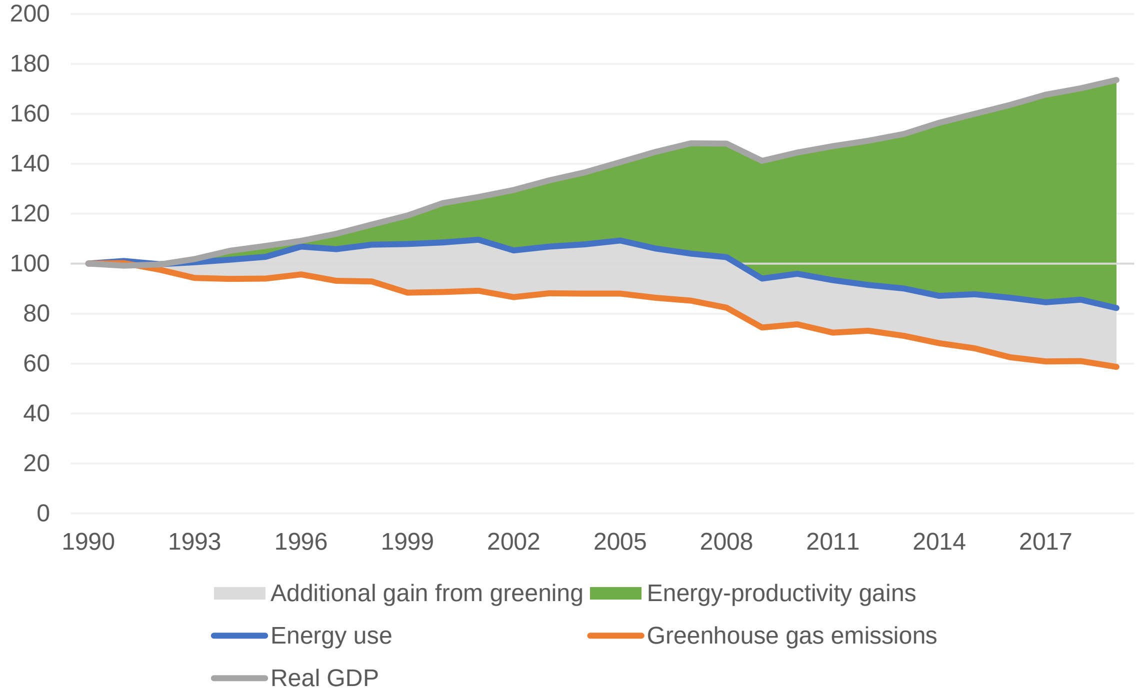
Emissions are in volume terms, namely tonnes of carbon dioxide equivalent. The emissions-productivity measures therefore represent the volume of economic output (GVA in volume terms) that can be produced per tonne of carbon dioxide equivalent emitted, irrespective of the price (or cost) one attributes to those emissions.

Emissions data for 2020 is only available at industry-section level, so we estimate the breakdown below this using the pattern from 2019 and the growth in industry GVA between 2019 and 2020, constrained to data at industry-section level. This implicitly assumes that emissions-productivity changes of an industry-section are representative of all the underlying industry-divisions. This may transpire to be a poor assumption, especially given the disruption caused by the coronavirus pandemic in 2020. However, we felt it was sufficient for the low-level industry breakdowns for just one year. In some charts below, we restrict our timeframe to end in 2019 to avoid distortion from including 2020.

5.2 Results

Emissions have fallen faster than energy use for the UK economy since 1990. Figure 4 shows real GDP, energy use, and emissions, all indexed to 1990. Real GDP (excluding imputed rental) grew nearly 75% between 1990 and 2019, while energy use fell about 18%. The difference between these growth rates are the gains in energy-productivity illustrated in section 4. The gains in emissions-productivity are greater than those in energy-productivity given that emissions per unit of energy used have fallen over this period. Emissions fell over 40% between 1990 and 2019 – more than twice as much as energy use. Thus emissions-productivity has grown by 150%, reflecting growth in energy-productivity and an additional contribution from the greening of energy sources used.

Figure 4 – Real GDP, energy use and greenhouse gas emissions, 1990 to 2019, index 1990 = 100



Notes: Real GDP excludes imputed rental, consistent with measures used elsewhere in this paper; it will therefore not match headline UK GDP.

As noted in section 5.1, these measures only relate to greenhouse gas emissions. Some energy sources may emit less greenhouse gases, but cause more pollutants, which are not captured here. Thus, there may be a trade-off inherent in the use of different energy sources, which Figure 4 does not capture.

As for energy-productivity, the majority of the growth in emissions-productivity comes from within-industry effects. Table 2 shows that between-industry effects (reflecting structural change in the economy) contributes between 13% and 21% of aggregate emissions-productivity growth, depending on the industry aggregation used. This is greater than the 9-18% for energy-productivity shown in Table 1, and suggests a relative decline in the size of industries with higher emissions per unit of energy used. However, 13-21% contributed by between-industry effects is still a minority of the aggregate growth.

Table 2 – Summary of within-industry and between-industry contributions to aggregate UK emissions-productivity growth 1990-2019, three industry aggregations

	Aggregation 1	**Aggregation 2**	**Aggregation 3**
Within			
Log points	85	91	95
% of total	78.7	83.6	87.4
Between			
Log points	23	18	14
% of total	21.3	16.4	12.6

Notes: In log points rather than percentages, for additivity. Aggregation 1 is most detailed (42), Aggregation 2 is section-level (20), Aggregation 3 is least detailed (6). See section 4.1 for details.

The majority of industries saw emissions-productivity growth between 1990 and 2019, with most industries also reducing their emissions in that time. Only a handful of industries did not reduce their emissions between 1990 and 2019 – rail transport [industry 49.1-2], air transport [division 51], real estate [section L], retail and wholesale [section G], admin services [section N], support services to transport (e.g. airports) [division 52], accommodation and food services [section I], forestry [division 02], extraction of oil [division 06], construction [section F], postal and courier services [division 53], and water supply [division 35].

Figure 5 – Average annual growth rates of energy-productivity and emissions-productivity between 1990 and 2019, by industry

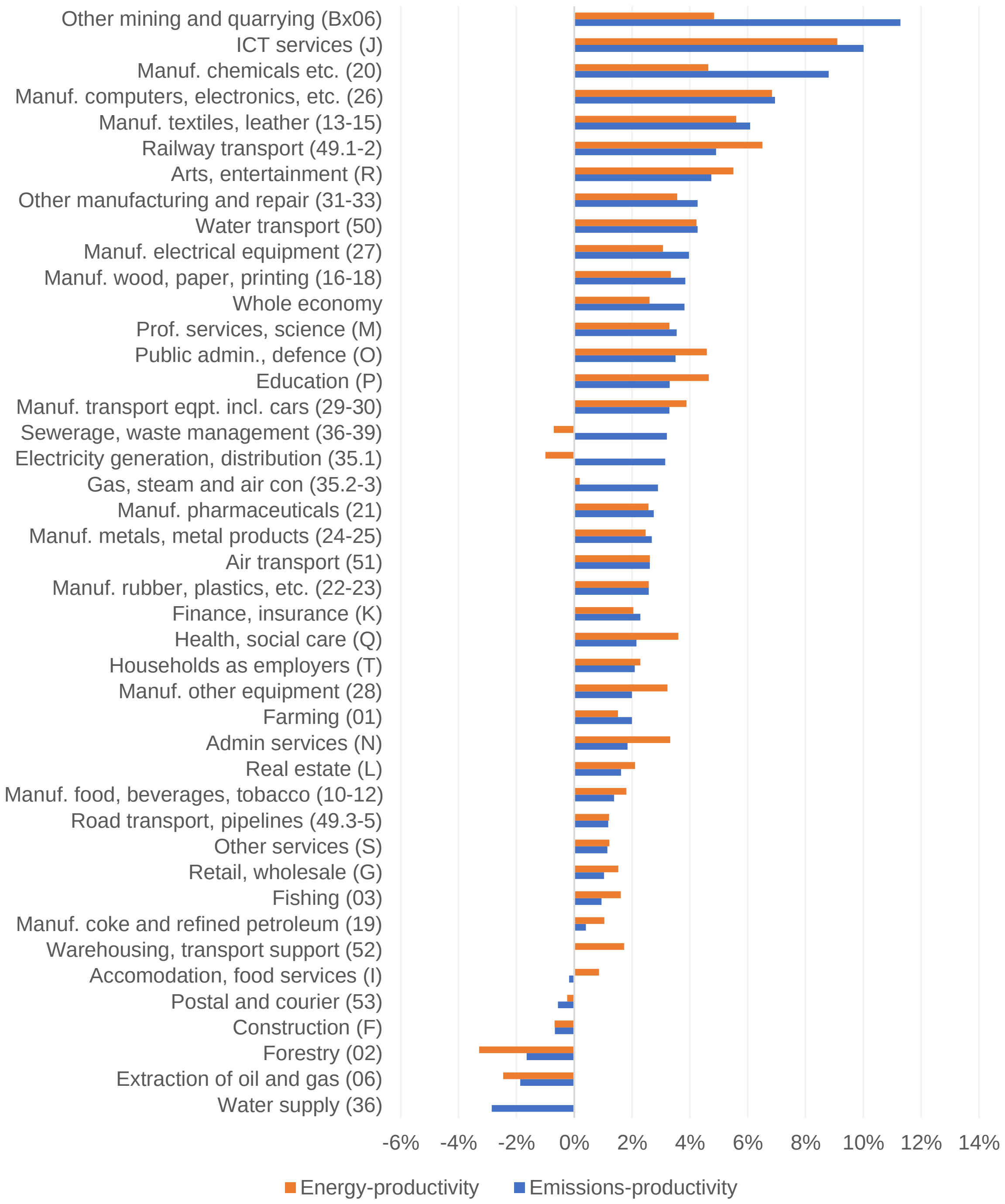


Figure 5 compares the average annual growth of emission-productivity and energy-productivity of each industry between 1990 and 2019. In most cases emissions-productivity grew faster than energy-productivity, reflecting changes in the energy mix used towards sources with lower average emissions per unit of energy, such as renewables. For instance, the electricity [industry 35.1] and gas, steam and air conditioning [industry 35.2-3] industries saw declines in energy-productivity but increases in emissions-productivity, reflecting a ‘greening’ of their energy mixes. Other industries to see substantial ‘greening’ of their energy use were the waste management [divisions 37-39], mining and quarrying other than oil extraction [divisions 05, 07, 08, 09], and manufacturing of coke and petroleum products [division 19].

Some industries saw a change in their energy mix which led to more emissions, and thus emissions-productivity grew by less than energy-productivity. Many of these are services industries, including all of the industries with substantial government activity – public administration and defence [section O], education [section P], and health and social care [section Q].

There is a wide range of outcomes within the transport industry. Rail, air, and water transport industries have seen large increases in energy-productivity, especially since 2009. Meanwhile road transport has seen much smaller increase, and a fall since 2009. Postal and courier services, which is largely by road, has also seen a decrease. This pattern mirrors the growth rates in GVA, but there are also differences in the pattern of emissions, with water and rail transport industries cutting emissions since 2009. Time series charts of emissions-productivity for all industries are shown in Annex C.

Table 3 – annual average growth of emissions, GVA, and emissions-productivity for transport industries, by period

	Emissions			**GVA (CVM)**			**Emissions-productivity**		
	1990-2019	1990-2007	2009-2019	1990-2019	1990-2007	2009-2019	1990-2019	1990-2007	2009-2019
Railway transport (49.1-2)	0.6%	1.9%	-1.1%	5.5%	6.6%	4.0%	4.9%	4.7%	5.1%
Road transport, pipelines (49.3-5)	-0.2%	0.3%	0.3%	0.9%	2.5%	0.1%	1.2%	2.2%	-0.3%
Water transport (50)	-2.0%	0.3%	-4.6%	2.2%	2.0%	4.4%	4.3%	1.7%	9.4%
Air transport (51)	2.6%	4.6%	0.3%	5.3%	6.7%	9.4%	2.6%	2.0%	9.0%
Warehousing, transport support (52)	1.3%	1.3%	2.1%	1.3%	1.7%	0.7%	0.0%	0.4%	-1.3%
Postal and courier (53)	1.6%	1.0%	2.1%	1.0%	2.2%	-0.7%	-0.6%	1.2%	-2.7%
Transport and storage (H)	*0.7%*	*2.1%*	*-0.5%*	*1.9%*	*2.9%*	*1.4%*	*1.2%*	*0.9%*	*1.9%*

6. Labour productivity with bad outputs

In National Accounts there are no negative outputs – goods and services that sell for a positive price lead to positive output, and if a good or service does not sell[5] for a positive price it makes no contribution. While it is possible for the cost of intermediate inputs to exceed the value of output, yielding negative GVA, output (revenue) here is still positive or zero. We diverge from national accounting rules to consider the treatment of greenhouse gas emissions as a negative output, and thus a deduction from GVA.

A question arises as to how to value the 'bad' output of emissions with respect to the 'good' output of GVA. The environmental literature often uses a Malmquist Data Envelopment Analysis (DEA) approach, which partially sidesteps this issue through the estimation of a distance function that solves for the relevant weighting of good and bad outputs (see for example, Pollitt 2022). We estimate this more directly by using a price per unit of emissions to estimate a cost, and adjusting GVA directly.

6.1 Data and methods

The bad outputs we adjust for are greenhouse gas emissions, acid rain precursors, and other pollutants. The emissions data is as described in section 5.1. The data acid rain percussors and other pollutants also come from ONS tables, sourced from Ricardo Energy and Environment. These data are all in volumes, although the volumes differ between the varies gases and pollutants. The full list of gases and pollutants covered is summarised in Table 4.

Table 4 – Summary of emissions and pollutants, including data sources

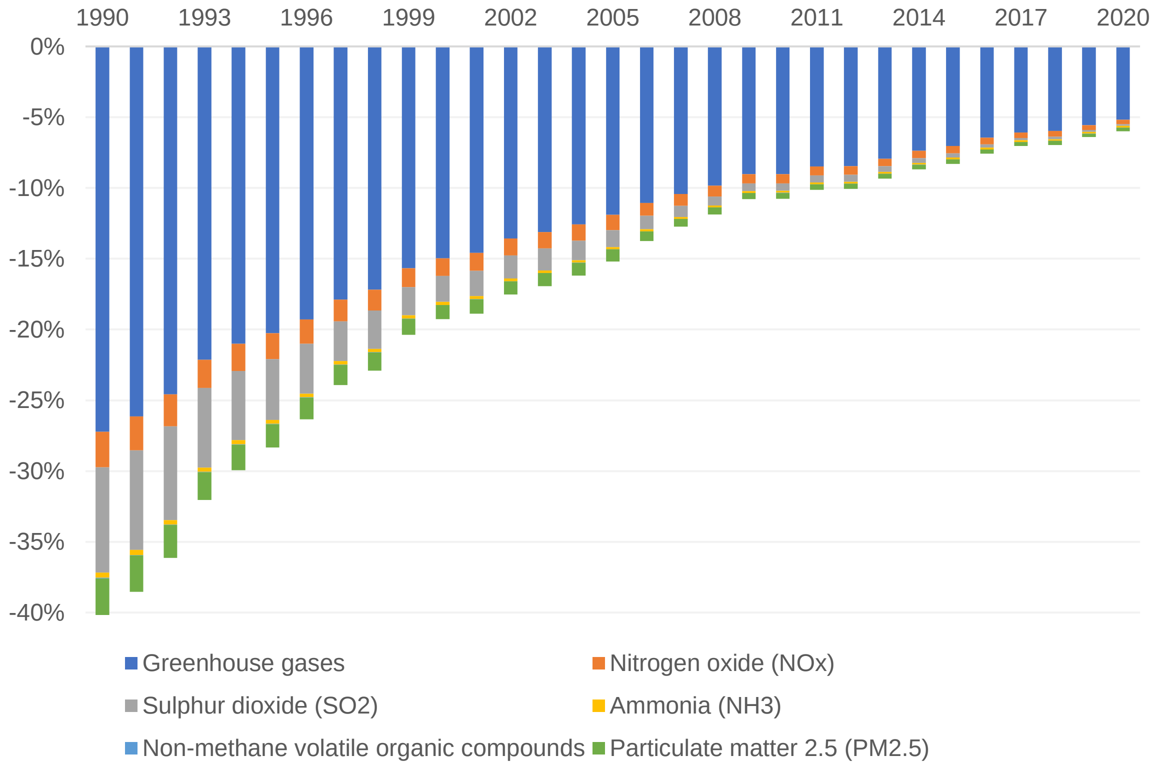
Category	Type	Price data source	Price per tonne in base year	Assumed price growth per year	Total fall in volume 1990-2019
Greenhouse gases	All	BEIS	£241 (2020)	1.5%	41%
Acid rain precursors	Nitrogen oxide (NO_x)	Defra	£6,383 (2017)	2%	67%
	Sulphur dioxide (SO_2)	Defra	£13,206 (2017)	2%	95%
	Ammonia (NH_3)	Defra	£7,923 (2017)	2%	17%
Other pollutants	Non-methane volatile organic compounds	Defra	£102 (2017)	2%	68%
	Particulate matter (PM2.5)	Defra	£73,403 (2017)	2%	78%

[5] There are also non-market outputs, which do not sell but are given freely, and output for own final use, which do not sell and are kept by the producer. However, these are both positive outputs, and have a positive shadow price, usually estimated by the costs of production.

To value the cost of the 'bad outputs' we multiply the volumes of emissions and pollutants by unit prices. We use UK government prices, published by the Department for Business, Energy and Industrial Strategy (BEIS) for carbon, and by the Department for Environment, Food, and Rural Affairs (Defra) for all other pollutants. The BEIS carbon price is the 2021 updated price, which is measured on a "mitigation cost" basis. This means the price is set so as to meet a policy goal, namely the UK government target to achieve Net Zero by 2050. The 2021 carbon price is therefore substantially higher than the previous carbon price, and higher than used in many previous studies. See Annex A for a discussion.

The prices for the pollutants are not measured in quite the same way. They are largely values translated from studies in the US based on econometric methods. As such, they may be small relative to the carbon price, and thus lead us to give too much weight to greenhouse gas emissions relative to acid rain precursors and other pollutants. Figure 6 shows the weight of the various gases and pollutants in adjusted-GDP, for the whole economy. These are negative, since they deduct from GDP[6]. Greenhouse gases (collectively, all measured in tonnes of carbon dioxide equivalent, and valued by the 2021 BEIS carbon price) dominate throughout, accounting for around two-thirds of the "bad outputs" in 1997, rising to over 85% in 2020. Their relative share of the "bad outputs" increases over time as the volume of the other pollutants fall more rapidly.

<u>Figure 6 – Contributions to adjusted-GDP by emissions and pollutant type, 1990 to 2020</u>



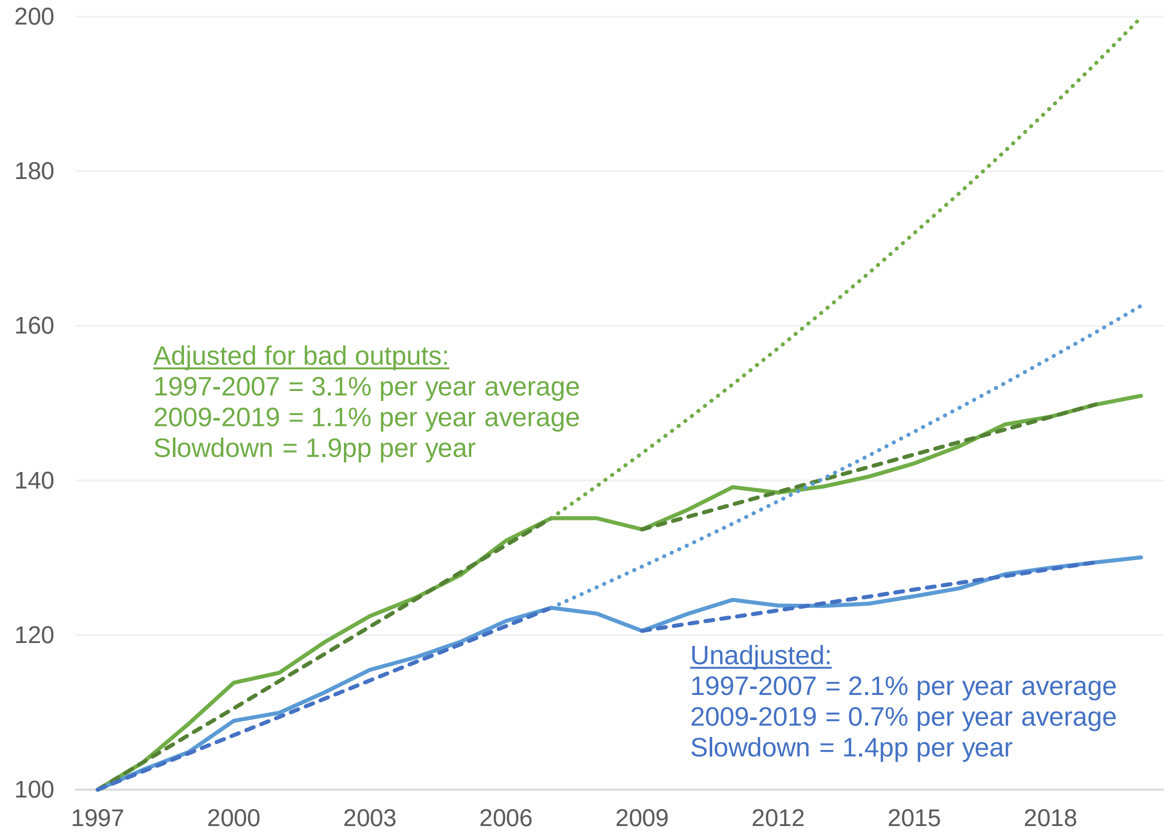
[6] The corresponding weight for unadjusted GDP is greater than 100%.

6.2 Results

Given the rapid decline in emissions and pollutant volumes, as detailed in Table 4, GVA adjusted for these bad outputs grows faster than unadjusted GVA. And since there are no changes to labour inputs, the changes to GVA have commensurate effects on productivity. Thus, labour productivity adjusted for bad outputs grows faster than unadjusted GVA.

Figure 7 shows labour productivity, with and without the adjustment for bad outputs, for the whole economy. The adjusted series grows faster than the unadjusted series. However, it grows faster both before and after the 2008 economic downturn, such that it does not narrow or 'solve' the "productivity puzzle" of a slowdown in productivity growth since 2008. In fact, adjusting for bad outputs widens the puzzle, since the increment to productivity growth before 2008 is larger than the increment after 2008. The slowdown increases from 1.4 percentage points of annual growth in the unadjusted series, to 1.9 percentage points in the adjusted series.

Figure 7 – Whole economy labour productivity, with and without adjustment for bad outputs, with pre-downturn trends, 1997 to 2020

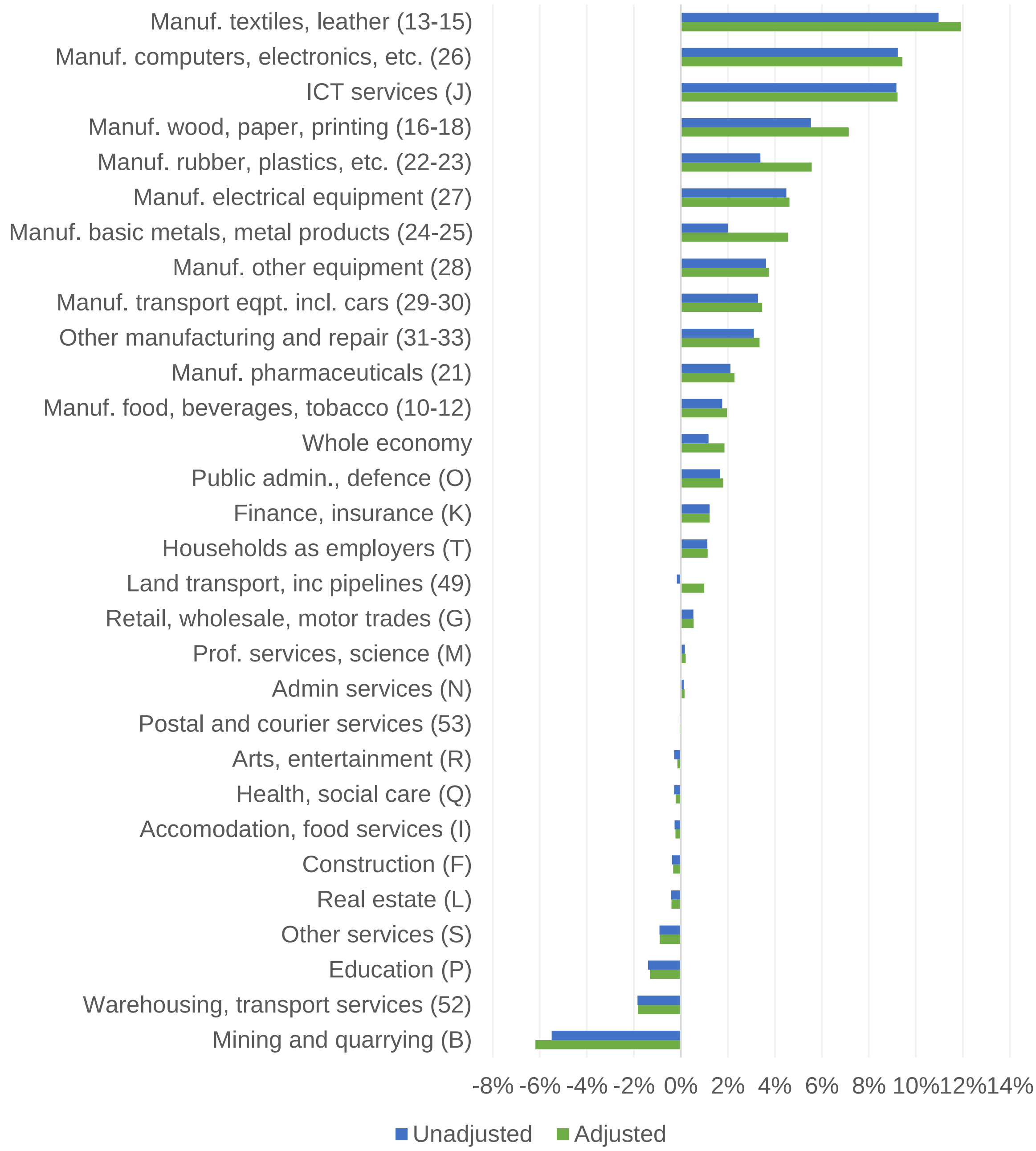


Notes: Pre-downturn trend calculated as the compound average annual growth rate from 1997 to 2007. Projection assumes this rate of growth continues from 2007 onwards.

The effects vary substantially by industry depending on the volume of emissions and pollutants relative to (measured) GVA, and the trend in the emissions and pollutants relative to the trend in real GVA. In some industries, the adjustments are so large (i.e., the volumes of emissions and pollutants are so large relative to GVA), that adjusted GVA turns negative. That is the case in the following industries and years:

- Agriculture, forestry and fishing (section A) – 1990-2013, 2015-2020
- Manufacturing of coke and petroleum products (division 19) – 1990-2020
- Manufacturing of chemicals and chemical products – 1990-1991
- Electricity, gas, steam, air condition (section D) – 1990-2016
- Water, sewerage and waste (section E) – 1990-1998
- Water transport (division 50) – 1990-2016, 2018
- Air transport (division 51) – 1990-2020

Figure 8 – Average annual productivity growth between 1997 and 2019, with and without adjustment for bad outputs, by industry



Notes: Productivity for industries with negative GVA levels after adjusting for bad outputs cannot be shown in growth rate space, so are omitted from the chart (see text for details). Growth rates to 2019 are shown to avoid the effects of the coronavirus pandemic.

Most industries see faster productivity growth after adjusting for bad outputs, although the effect is small in many services industries. Figure 8 shows average annual productivity growth between 1997 and 2019, with and without the adjustment for bad outputs, by industry[7]. The median industry sees 0.1 percentage points faster productivity growth per year between 1997 and 2019 after adjusting for bad outputs. The mean effect is 0.3 percentage points, driven by large effects in a few industries, while most see much smaller effects.

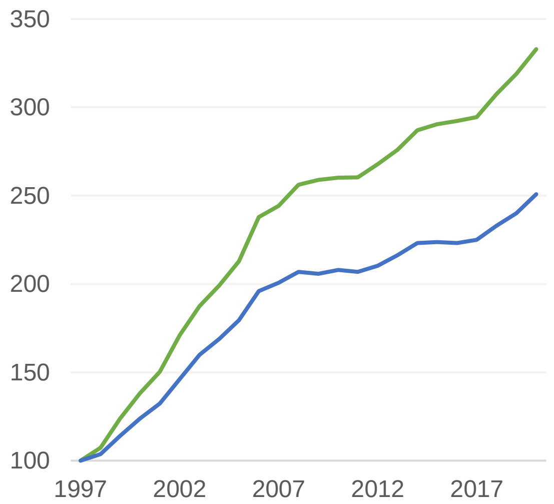
Only two industries see slower productivity growth between 1997 and 2019 after adjusting for bad outputs: mining and quarrying (section B), and postal and courier services (division 53). Mining and quarrying (section B) is dominated by oil and gas extraction (division 06), both in terms of size and trends in emissions and energy use (see Annex B and C). Oil and gas extraction (division 06) and postal and courier services division 53) were two of only a handful of industries to see declining energy-productivity and emissions-productivity, and to see increased energy-use and emissions in absolute terms between 1997 and 2019.

The adjustment for bad outputs leads to slower productivity growth for a few other industries in selected periods (although not across 1997 to 2019 as a whole), including several manufacturing industries since 2009. In line with the whole economy (Figure 7) the effects of the adjustment are smaller after the 2008 economic downturn than before for the median industry.

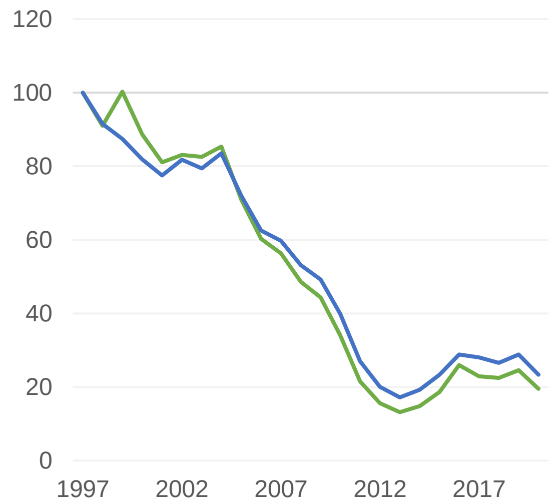
Figure 9 shows labour productivity with and without the adjustment for bad outputs as an index where 1997 equals 100, for selected industries. In manufacturing (Figure 9a) and services (Figure 9c), labour productivity grows faster after adjusting for bad outputs, but in both cases still sees a slowdown after the 2008 economic downturn. Charts for all other industries are in Annex D.

Figure 9 – Labour productivity with and without adjustment for bad outputs, selected industries, 1997 to 2020, index 1997 = 100

9a – Manufacturing (C)

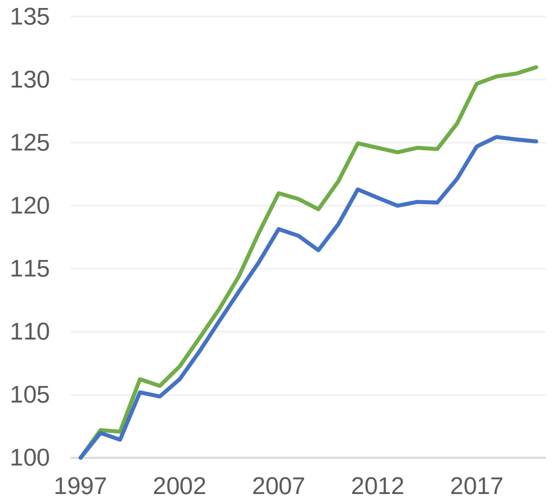


9b – Mining and quarrying (B)

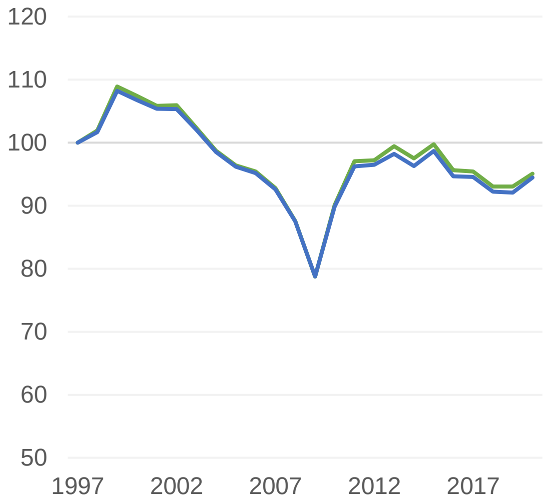


[7] The industries with negative adjusted GVA, listed above, are omitted from Figure 8 since CVMs and indices cannot be calculated for these industries.

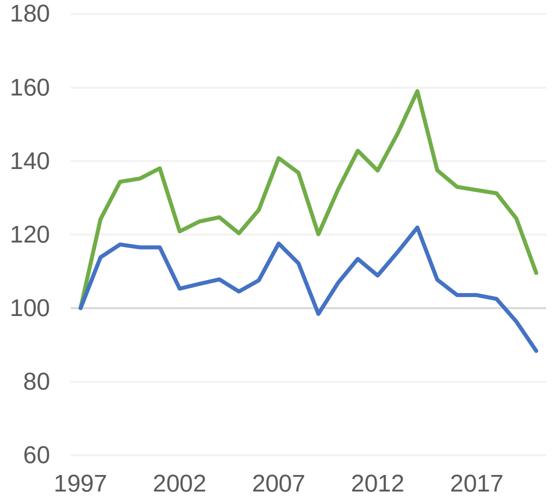
9c – Services (G-T)



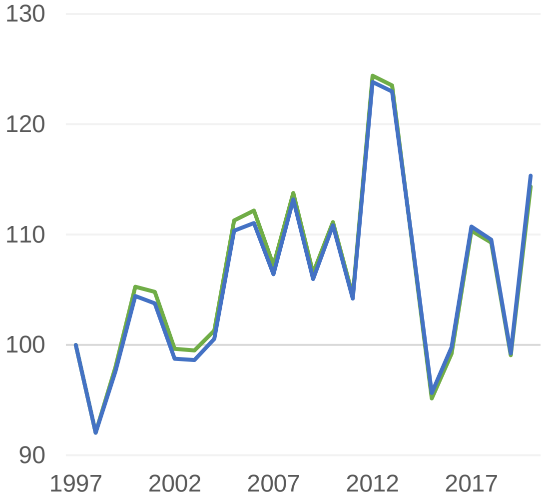
9d – Construction (F)



9e – Land transport (49)



9f – Postal and courier services (53)



Notes: Scales vary between charts. Selected industries shown here, all other industries shown in Annex D. Productivity for industries with negative GVA levels after adjusting for bad outputs cannot be shown in growth rate space, so are shown in levels in Annex D.

7. Labour productivity with unmeasured environmental protection output

While the adjustment for bad outputs in section 6 is concerned with better reflecting the social value of measured output, section 7 is concerned with adjusting for additional unmeasured output. Specifically, we adjust GVA to account for unmeasured output in the form of environment protection.

In national accounting, three types of output exist:

- market output (sales on the market for a price; the majority of output)
- output for own-final use (output produced for use by the business, that could have been purchased on the market – for instance, development of software assets by own staff)

- other non-market output (output produced and given away for free or non-economical prices, such as education services produced by government)

Businesses can incur costs to protect the environment, but are not usually compensated for them. They incur these costs either due to regulatory requirements, or because they choose to, perhaps because they feel a social obligation to do so, or as a form of branding. Regardless of why, these costs are borne but no corresponding output is recorded. This is a form of (unmeasured) non-market output. Whether it is treated as output for own-final use or other non-market output, capturing these costs as output would increase GVA by a corresponding amount. We can consider these costs as investment in the environment as an asset, and while the business will not exclusively benefit, there is clearly value generated for the economy and society. This type of expenditure is sometimes known as 'defensive expenditure' in the environmental economics literature.

Since this output requires inputs, failure to measure the output biases measured productivity down. This is because the inputs (e.g., hours worked by labour) are measured and included in the denominator of the productivity equation, but the corresponding output is not recorded in the numerator. Thus, the hours worked appear to be entirely unproductive – they produce no (measured) output. We explicitly measure the (currently unmeasured) environmental protection output produced by businesses, add it to (measured) GVA, and recalculate productivity.

7.1 Data and methods

Non-market output and output for own-final use are usually measured in the national accounts by the costs of production, or "sum of costs" method. This involves estimating and summing all the relevant costs of producing the output. This yields the current price estimate of the value of the output, which can then be deflated by a suitable price index to give a constant price series.

We follow the approach used to estimate capital investment in own-account software in the national accounts. This involves identifying relevant occupations that perform environmental protection activities in their role, estimating a fraction of their time spent doing so, and treating this fraction of their wages as part of the costs of producing environmental protection output.

For the occupations and time factors we use Martin and Monahan (2022a) which estimated time spent on "green tasks" by occupation in the UK. This study used task-level data for detailed occupations from the US O*NET database, mapped to UK occupation classifications. The O*NET database contains detailed task information for around 1,000 occupations, based on surveys of incumbent workers and occupational experts. Each task has a corresponding "relevance" and "frequency" score, which Martin and Monahan (2022a) translated into an estimate of the average proportion of time spent on that task. Tasks that were "green" (following the classification introduced in O*NET (2011), and extended for earlier and recent years using a combination of automated and manual coding) were tagged, and thus the average proportion of time spent on "green tasks", by occupation, calculated. To give a full time-series by occupation, the green time shares were interpolated and extrapolated. They were then converted from the US occupation classification to the UK Standard Occupational

Classification (SOC), via the international occupation classification (ISCO), and then applied to UK labour market data. For more details, see Martin and Monahan (2022a), which is summarised in Annex E.

We extend Martin and Monahan (2022a) by applying the green time shares by occupation to the Annual Survey of Hours and Earnings (ASHE). We can then estimate the labour costs associated with these "green tasks", by multiplying the time proportions by the reported wages and salaries. Since this reflects only labour costs, we then adjust for non-wage labour costs (such as pension contributions and employers' National Insurance contributions), and for non-labour costs (such as materials, overheads and cost of capital), and apply a mark-up for net operating surplus (a profit margin). We vary this uplift factor for non-labour costs by occupation to account for the type of environment protection tasks they are doing, and thus the likely cost structure of their activity. See Annex E for more details. This gives the total value of environmental protection expenditure in the UK.

Table 5 – Overlaps between environmental protection output and GDP

Channel of overlap	**Adjustment method**	**Impact**
Household final consumption expenditure	Purchases of machinery and equipment, including transport equipment, repair and maintenance of that equipment, and construction; multiplied by the proportion of hours spent on green tasks in the corresponding industries (manufacturing and construction)	4-5%, flat
General government final consumption expenditure	All environmental protection output of the public admin and defence industry (section O), and half from the education (section P), and health and social care (section Q) industries	6-9%, falling then flat
Exports of services	Exports of mining support services, repair and maintenance of equipment, waste collection and treatment services, construction, consultancy, architectural and engineering services and other professional, scientific and technical services, all multiplied by the proportion of hours spent on green tasks in the corresponding industries	1-3%, rising
Gross fixed capital formation: R&D	R&D in agriculture, mining, manufacturing of coke and petroleum, motor vehicles and parts, other transport equipment, waste management, energy, construction, transport, and miscellaneous business services, multiplied by assumed "green" factors ranging from 10% to 100%	c. 1%, rising
Gross fixed capital formation: other assets	Investment in machinery and equipment, transport equipment, and buildings and structures, multiplied by the proportion of hours spent on green tasks in the corresponding industries (manufacturing and construction)	12-19%, rising

Notes: Impact relates to the deduction from total environmental protection output. Data for adjustments sourced from ONS Supply and Use Tables, Business Expenditure on R&D, Martin and Monahan (2022b), and authors' calculations. No adjustments made for exports of goods, NPISH final consumption expenditure, acquisitions less disposals of valuables, or changes in inventories. See Annex E for more details.

However, some of this cost will already be captured in GDP if it contributes to final demand. For instance, if our estimates of environment protection output include the value of environmental consulting services produced by UK firms and exported, then it will already be in GDP, and we would not want to double count this. Many forms of double-counting are possible, but we judge some more likely than others. Table 5 summarises the channels of double counting we identified and our approaches to adjusting for them.

If our estimates overlap with intermediate consumption, then this will not lead to double counting. Purchases of goods or services by UK businesses that are currently treated as intermediate consumption are captured in the National Accounts, but do not contribute to GDP, as intermediate consumption is deducted from total output to calculate GVA. By adding this to GDP, we are effectively reclassifying it from intermediate consumption to final consumption, which means it is no longer deducted and thus adds to GDP. This is similar to the conceptualisation of uncapitalised intangible investment adding to GDP, either as output for own-final use in the cast of own-account investment, or reclassified intermediate consumption in the case of purchased investment (see, e.g., Goodridge, Haskel and Wallis, 2016).

Finally, we need a price index for the unmeasured environmental protection output. This output is likely very heterogeneous, reflecting the mix of "green tasks" identified in the O*NET database used by Martin and Monahan (2022a). This also reflects the range of environmental protection activities that businesses in different industries could undertake – in production industries this could relate to reducing emissions from machinery and equipment, or using greener materials; in services industries this could relate to changes in business practices, changes to supply chains, or researching more environmentally-friendly investments. Reflecting this heterogeneity, we construct a composite price index which reflects four types of output, weighted equally:

- maintenance and repair of machinery and equipment, including cars and other manufacturing machinery – reflecting activities to make environmental amendments to existing assets, such as the fitting of filters
- waste treatment and management – reflecting activities to reduce the environmental damage of waste from production activities, through recycling, material reclaim and other waste management techniques
- architectural and engineering services – reflecting activities to design and plan more environmentally-friendly buildings, infrastructure and urban areas, including for cleaner sources of transport
- consultancy and other professional services – reflecting activities to monitor, review and change business practices, supply chains and strategies to be more environmentally-friendly

Each of these relies on a range of producer price indices (PPIs), services produce price indices (SPPIs), and industry output deflators. Full details are in Annex E.

The adjustment to GDP is thus the full cost (labour costs plus uplift for non-wage labour costs) of environmental protection output, less adjustment to avoid double counting with measured final demand. For constant price (volume) estimates, these are then deflated using our composite price index. The unmeasured environmental protection output is combined with GDP in a chained volume measure (CVM), by using the weights of unadjusted-GDP and the unmeasured output in adjusted-GDP in the base period and the growth in the volumes of GDP and the unmeasured output respectively.

No changes are made to inputs, so adjustments to GDP translate one-for-one into adjustments to labour productivity.

7.2 Results

Martin and Monahan (2022b) estimate that 7-8% of hours worked in the economy are spent on “green tasks” in 2019. This has increased over time, from around 5-6% between 1997 and 2010. The workers completing the green tasks are skewed towards professional, technical and managerial occupations, and are paid above average. Thus, the wages associated with these hours represent more than 7-8% of total labour compensation. Once accounting for the cost uplifts described in section 7.1, our estimate of environmental protection output is equivalent to about 11% of GDP (excluding imputed rental) in 2019, up from about 9% in the decade to 2007.

However, this is not all additional to GDP, since we need to adjust for the share of this output that is already recorded in GDP, as described in section 7.1. Once adjusting for double counting, the unmeasured environmental protection output adds about 6-7% to the level of GDP (excluding imputed rental) between 1997 and 2019.

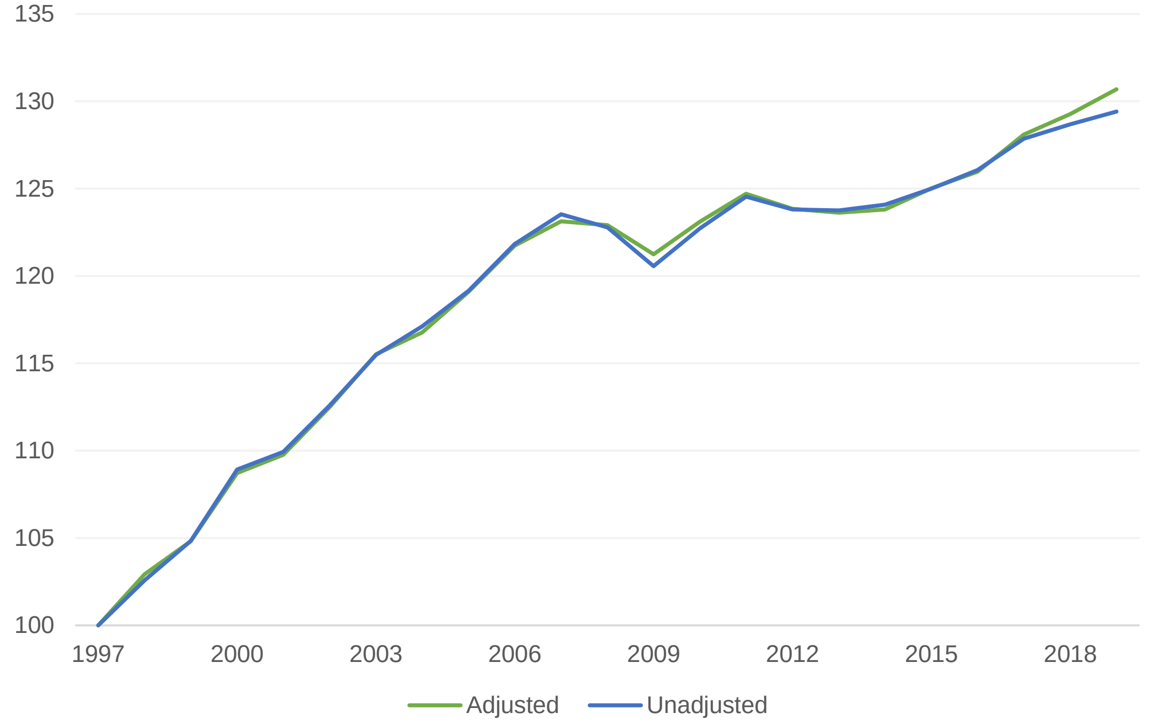
This adjustment would not explain why the UK appears to have a lower level of labour productivity than other developed economies (see, for instance, ONS, 2021). Environmental protection output is currently not included in GDP in any countries, following international national accounting guidance. Including this for the UK would necessitate doing so also for other countries in order to make a fair comparison. It is possible that the UK produces relatively more unmeasured environmental protection output than other countries, such that adjusting in all countries would boost the UK’s relative position. It is beyond the scope of this paper to test this.

In terms of growth, UK labour productivity grows slightly faster between 1997 and 2019 after adjusting for unmeasured environmental protection output. Differences earlier in the period are smaller, reflecting a slightly smaller weight of the environmental protection output in adjusted-GDP, and a similar growth rate (in volume terms) to GDP. Differences are largest from 2017 to 2019, when growth almost doubles: from 0.6% per year on average, to 1.0%. This by no means closes the “productivity puzzle”, but provides tentative evidence for a source of unmeasured growth in recent years.

Figure 11 compares annual growth rates of unadjusted GDP, the unmeasured environmental protection output, and adjusted GDP, in current prices, chained volume measures, and deflators. The series for the unmeasured environmental protection output are more volatile than GDP before or after adjustment, reflecting data quality and uncertainty in the measurement. However, the average growth rates of the unmeasured environmental protection output are similar to unadjusted GDP in both current prices and chained volume measures, which is reassuring.

The reason that adjusted-GDP (and hence adjusted labour productivity) grows faster between 2017 and 2019 than unadjusted-GDP is a combination of faster current price growth, and a weaker deflator.

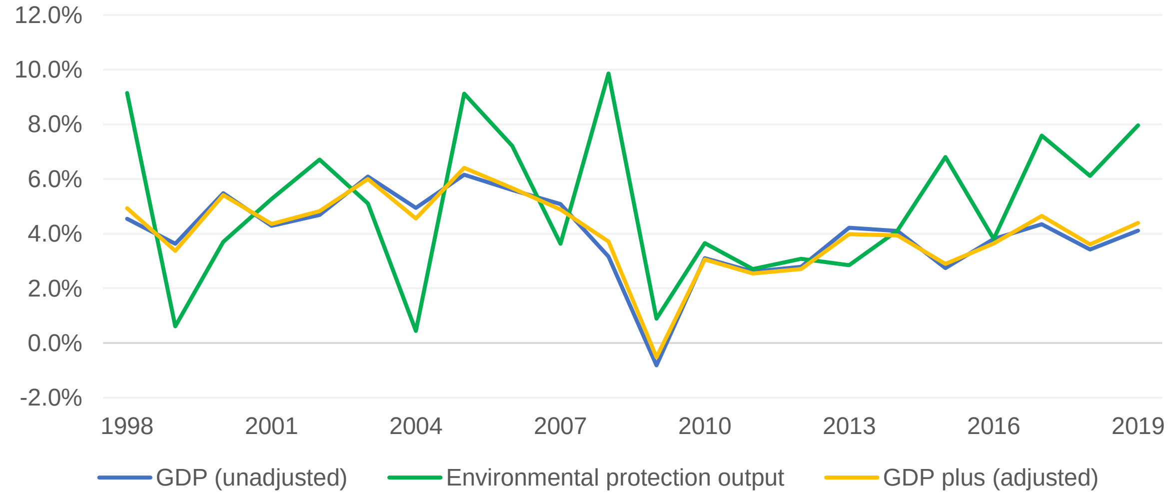
Figure 10 – Labour productivity with and without adjustment for unmeasured environmental protection output, whole economy, 1997 to 2019, index 1997 = 100



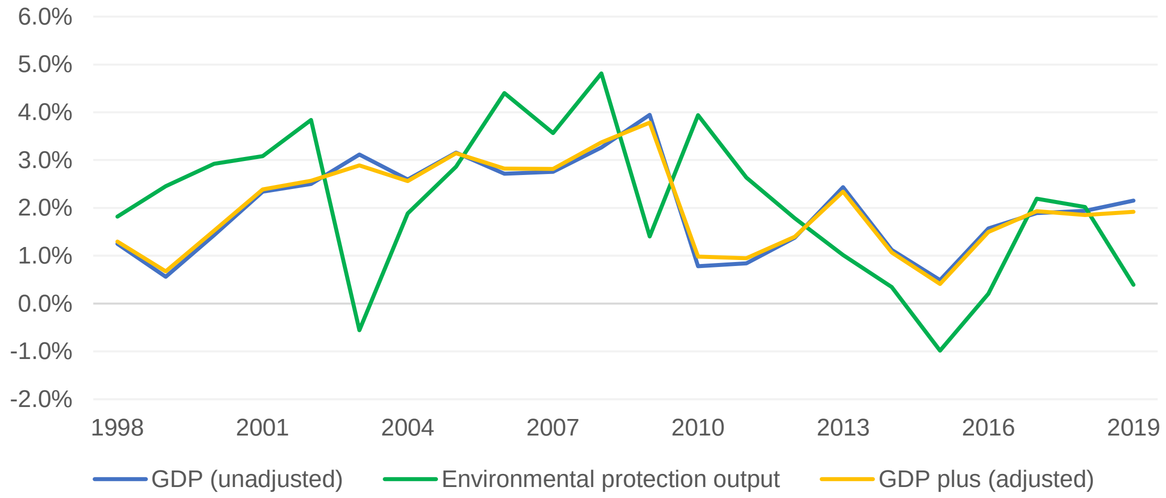
Notes: GDP excludes imputed rental, consistent with measures used elsewhere in this paper; it will therefore not match headline UK GDP.

Figure 11 – Annual growth rates of current prices, deflators, and chained volume measures for GDP with and without adjustment for unmeasured environmental protection output, 1997 to 2019

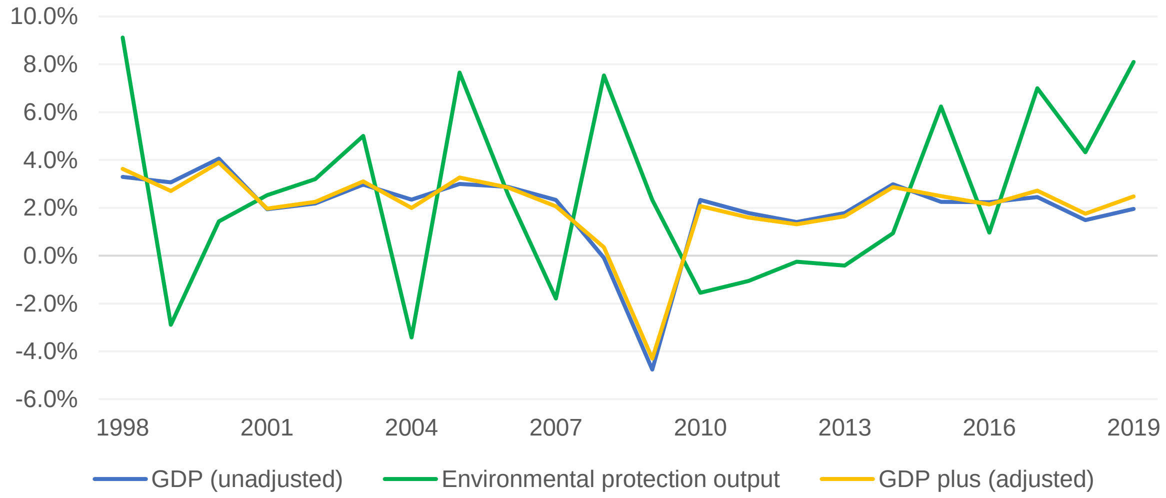
11a – Current prices (CP)



11b – Deflators



11c – Chained volume measures (CVM)



Notes: GDP excludes imputed rental, consistent with measures used elsewhere in this paper; it will therefore not match headline UK GDP. Deflator for adjusted-GDP is CP growth minus CVM growth.

8. Conclusion

In accordance with the spirit of the Dasgupta Review, we use SEEA-consistent data from the UK's natural capital and environmental accounts to recast core economic measures of productivity and GVA in a social welfare rather than purely private goods perspective. Focusing on the value of greenhouse gas emissions and non-greenhouse gas air pollutants, we construct measures of energy-productivity, emissions-productivity, labour productivity with GVA- (deducting the value of bad outputs), and labour productivity with GVA+ (adding the value of investments in environmental protection). We explore the implications of these adjusted measures for understanding the 'productivity puzzle' and provide highly disaggregated sectoral estimates of environmentally-adjusted productivity growth.

Our results show that incorporating emissions into productivity measures generally improves measured productivity growth in the UK in recent decades, but this varies across industries and environmentally-adjusted productivity measures. UK energy-productivity more than doubled between 1990 and 2019, and is overwhelmingly explained by within-industry improvements, though between-industry effects have grown since 2006. Further good news arises from the data on emissions productivity, which has grown 150% since 1990, reflecting both the improvement in energy productivity and a reduction in the emissions intensity of energy itself. To calculate environmentally-adjusted labour productivity net of pollution externalities, we make downward revisions to GVA, reflecting the value of GHGs and air pollution. Because these emissions have fallen rapidly over time, the resulting GVA- grows faster than standard GVA (because the magnitude of the downward revision is falling). This increases measured productivity growth. However, it does so both before and after the 2007-2009 financial crisis, so does not explain the productivity puzzle. Finally, we construct an environmentally-adjusted labour productivity measure that incorporates a ‘missing output’, that reflects a type of investment in environmental protection.

There are of course a range of caveats and opportunities for further work. This is largely a data-driven exercise and so the quality of the results depends first and foremost on the quality of the data. One concern is the potential for time lags between economic activity and its associated emissions. This could arise if, for instance, waste sent to landfill generates emissions over many years, or if there is a time lag between changes in agricultural land use (e.g., switching to regenerative agricultural practices that store carbon in soils over time, or planting trees as carbon offsets) and the ultimate impacts on emissions. Perhaps the greatest data challenge though relates to definitions of ‘green tasks’ and estimates of the costs incurred and benefits generated by them. This is an active area in environmental economics. Finally, there remains an ongoing debate about carbon pricing and the valuation of air pollutants. It is unavoidable, but the measures of environmentally-adjusted productivity growth are sensitive to the values used.

We hope that future work could extend the analysis in several ways. First, it would be good to incorporate a broader set of natural capital and environmental factors (good and bad) into the environmentally-adjusted productivity analysis. Second, we feel it would be useful to conduct the analyses within an environmentally-extended multi-regional input-output model so that leakage effects could be addressed. Finally, for guiding future investments in productivity and Net Zero, it will be important to consider how the relationships and generally win-win trends shown here might unfold over time. If the higher environmentally-adjusted productivity measures shown here represent the low-hanging fruit in terms of ‘greening’ the economy, then we could expect to see the gap between adjusted and traditional measures fall. Alternatively, it could be that greening the economy continues to deliver energy, emissions, and labour productivity gains long into the future.

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Annex A – Discussion of carbon prices

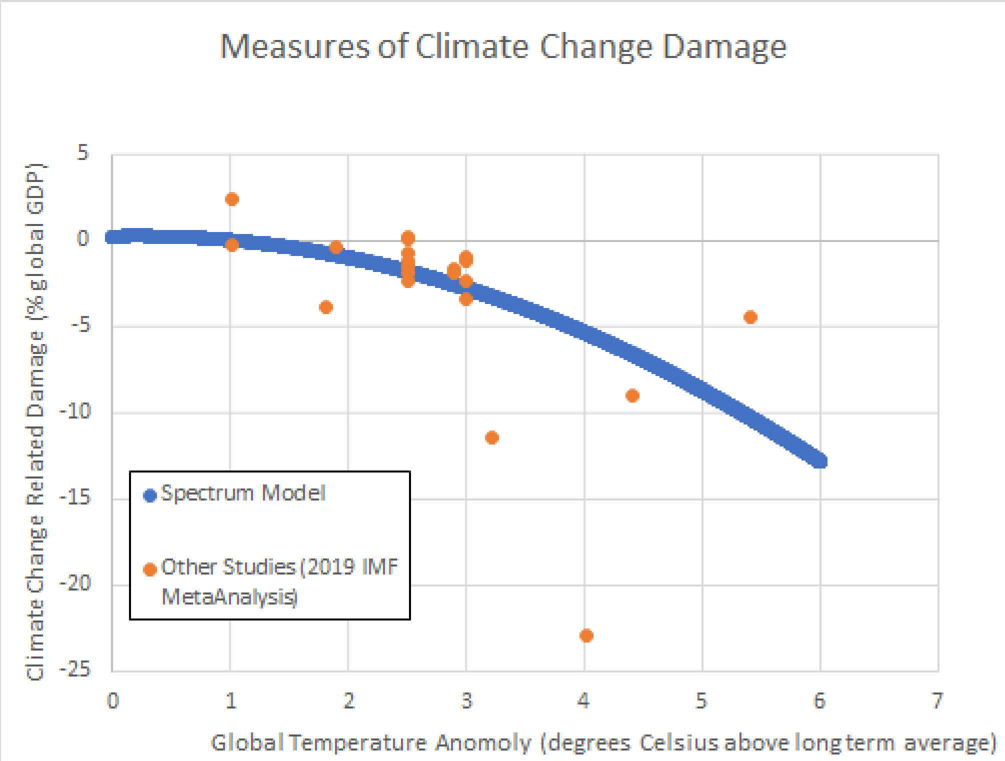
While ONS have undertaken extensive work to deliver ecosystem accounts and environmental asset valuations to meet policy maker and user needs, estimates of environmental asset depletion or degradation have not been produced to date. Depletion measures the amount of a natural resource extracted or used as part of economic production, while degradation adds to this the valuation of any loss of future ecosystem services due to the extraction / use of the natural resource in the current period. As set out in the System of Environmental-Economic Accounting (SEEA 2021), by subtracting degradation from measures of value added, national accounting frameworks can be adjusted to incorporate the (over-)use of environmental assets.

One simplified framework for thinking about the effect of climate change is to examine the atmosphere as an environmental asset, and consider carbon emissions as causing degradation of this asset – including both direct and indirect degradation. For example, some degradation of the atmosphere may impact and degrade the biosphere.

A version of this simplified framework was specified in Bucknall et al. (2021), employing a damage-based approach. Under this approach, the damage caused by, or embodied in, the degradation of an environmental asset is used to value the degradation. In our case, that means valuing the loss of economic output (as measured by GDP) estimated to be associated with global warming resulting from carbon emissions.

This valuation method was combined with a presentation approach, as outlined in section 12.3.3 of SEEA 2021, of “Polluter pays”. Under this method, the cost of the degradation is borne by the economic unit which caused the degradation. This method is useful where there are multiple contributors to degradation, and the effects of the degradation happen over a long timeframe – both of which are key features of atmosphere degradation due to climate change. Simply put, this presents the damage to the atmosphere caused by UK carbon emissions as being degradation in the UK’s accounts, regardless of who owns the atmosphere.

The model employed in Bucknall et al. (2021) can be summarised as follows: the degradation to the atmosphere caused by the UK in year x is equal to the discounted damage to global GDP in years x, x+1, x+2,… due to the marginal amount of warming caused as a result of the UK’s carbon emissions in year x (conditional on the starting temperature anomaly). As such, a key feature of this model is the relationship between global warming (as mentioned by the global temperature anomaly) and damage to global GDP. The paper repurposes and extrapolates this relationship using research from OECD (2015). While other research have found a broad spread of results for this relationship, the OECD work generally lies in the middle of the pack – and uses a quadratic function, as is common in the literature (Vivid Economics, 2021).



This approach to measuring the negative effect on “the economy” associated with climate change can be considered a sub-set of the broader literature around measuring ‘carbon prices’. ‘Carbon prices’ are prices which could be placed on carbon in order to manage carbon emissions, and bring about a socially desirable amount of carbon emissions. This desirable amount could be directly stated (such as seeking the carbon price which would induce net zero carbon emissions by a particular date) or indirectly stated (such as seeking a carbon price which would maximise social utility by equating the price of carbon with its negative externality).

The models of Bucknall et al. (2021), as well as others which seek to value the negative effect on “the economy” of climate change, can be interpreted as having endogenous carbon prices – which can be backed out by simply dividing the negative effect on “the economy” by the volume of carbon emissions. This would give a carbon price which, if charged, might maximise social utility (in a perfectly competitive economy, and assuming the damages have been calculated correctly).

However, doing so presents two informative options. On the one hand, the negative effect in one period could be divided by the emissions in that one period. Let’s refer to this as the ‘marginal’ approach – it uses the marginal effect, given the circumstances in that particular year, of the carbon emissions on global temperatures. To be clear, this still allows for the emissions in one year to cause ‘damages’ in future years. But, for example, if emissions in year x cause the global temperature anomaly to increase from 1.0 to 1.1, then the damage in years x, x+1, x+2, … will be based on an additional 0.1 degree of warming from 1.0 to 1.1 degrees *in all subsequent years* – i.e. regardless of the actual amount of warming in future years. Warming in future years is held constant. This produces the outcome, due to the quadratic damage function, that the same volume of emissions is valued as causing a smaller negative economic effect in previous (colder) years but a larger effect in future (warmer) years – this could be thought of as time inconsistent.

In contrast, one could take an 'average' approach to calculating a damage-based carbon price. If our models forecast carbon emissions, global GDP, and other variables far enough into the future such that it covers the entire period in which excess carbon emissions contribute to climate change, then it's possible to divide the total damage of climate change by total carbon emissions. This measure of the negative economic effect of climate change would be time invariant (in real terms, after adjusting for inflation) – remaining consistent across time, regardless of the global temperature anomaly in any particular year.

This latter, 'average' approach is of much more statistical and analytical interest than practical interest. The purpose of much carbon price analysis is to find the optimal price to apply to carbon in order achieve a socially desirable outcome *by affecting the decisions of economic agents*. While it may be obvious, only the current and future decisions of economic agents can be affected by pricing today. The 'marginal' approach prices carbon according to damage caused in a particular period in order to affect emission decisions and maximise welfare in that particular period – irrespective of past and future emissions. Simply put, as the past cannot be changed it ignores past (potentially non-optimal) carbon emissions and focusses purely on current damages and welfare. On the other hand, the 'average approach' considers the average damage caused per unit of carbon over the entire period – so pricing will be invariant over time, and will not be designed to maximise welfare at any point in time.

While the 'marginal' approach resultingly presents itself as of more interest to real world price-setting decisions, the 'average' approach presents an opportunity for interesting analysis, particularly of intertemporal inequality. The time inconsistency of the 'marginal' approach means that persons, institutions, or countries could be interpreted as causing less 'harm' to the environmental if the same volume of carbon was emitted earlier in time, and more 'harm' is caused if the same volume is produced in the (warmer) future. This could be interpreted as an inequity in the approach – and that for analytical reasons, it might be insightful to use an approach in which the damage caused by different bodies is not related to the period in which they emitted. The 'average' approach provides for just this kind of analysis.

A final approach for measuring a carbon price is explored in this article – the mitigation cost approach. This values carbon according to the price which would be required to induce carbon emissions of a pre-specified value – e.g. the price required to hit a certain target for emissions at some point in the future. As a result, this approach is of practical use, in particular in policy making. However, its statistical use – particularly when working in a national accounting framework – is smaller, as is not designed as a methodology for measuring degradation of an environmental asset[8]. As such, when used as a methodology to adjust economic output (as defined

[8] SEEA (UN 2021) recognises 3 approaches to measuring degradation. The first, explored in most detail, measures degradation in terms of the loss of future value of ecosystem services due to a decline in ecosystem condition – where the degradation is attributed to the economic unit who suffer the loss of the ecosystem services. The second approach (utilised in Bucknall et. al 2021) is commonly referred to as "polluter pays" and is a variation of the first approach where the degradation

using national accounts concepts, such as GVA), this stands as a methodologically inconsistent approach which should be treated with caution – but may still be of analytical interest bearing this in mind.

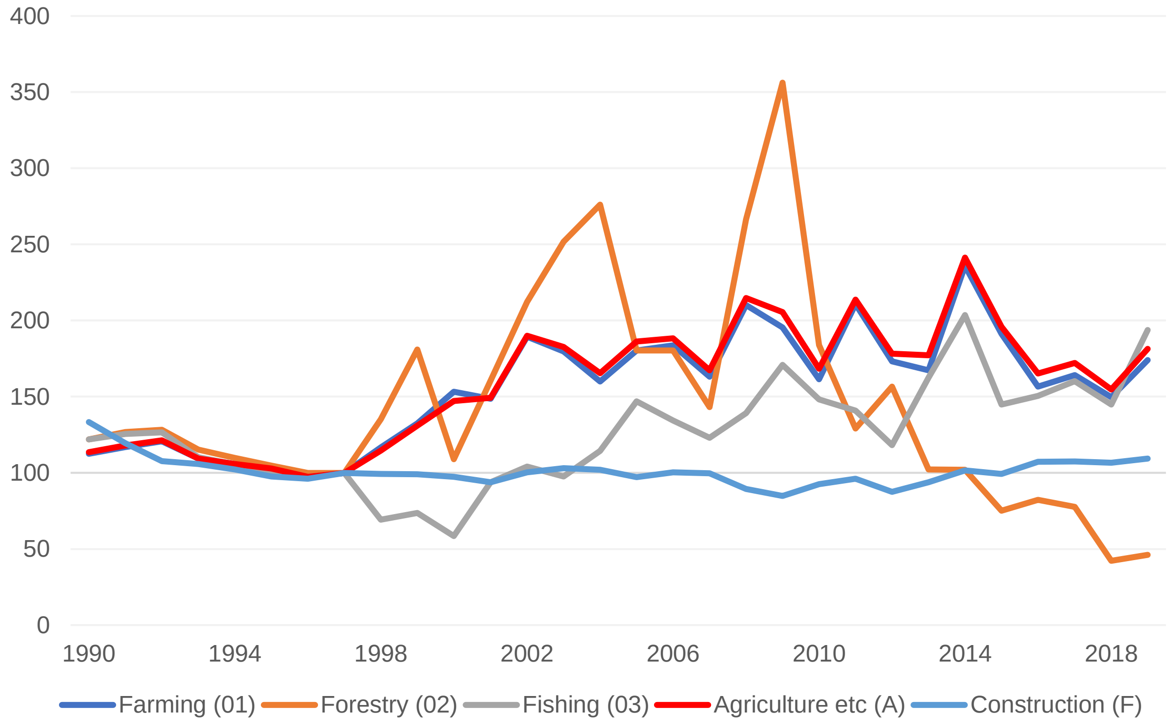
Empirical estimates of environmentally-adjusted economic output are presented in this article using these different approaches to measuring atmosphere degradation and carbon prices. The discussion above is intended to highlight that these approaches are all designed for different purposes which make some more methodologically preferable than others. But all approaches are presented for analytical purposes, rather than to imply they are all equally valid methodologically, to contribute to a discussion of how economic statistics could or should reflect the damage of climate change.

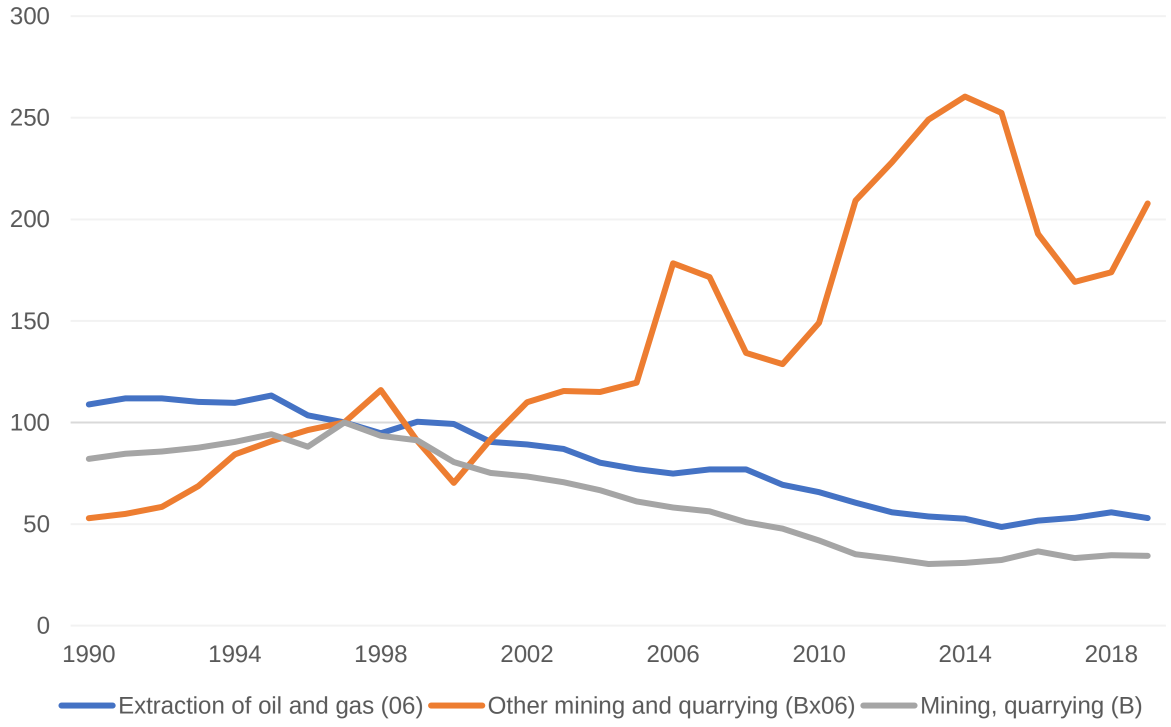
is attributed to the economic unit which caused the degradation. The third approach measures the cost of restoring an environmental asset to its previous condition.

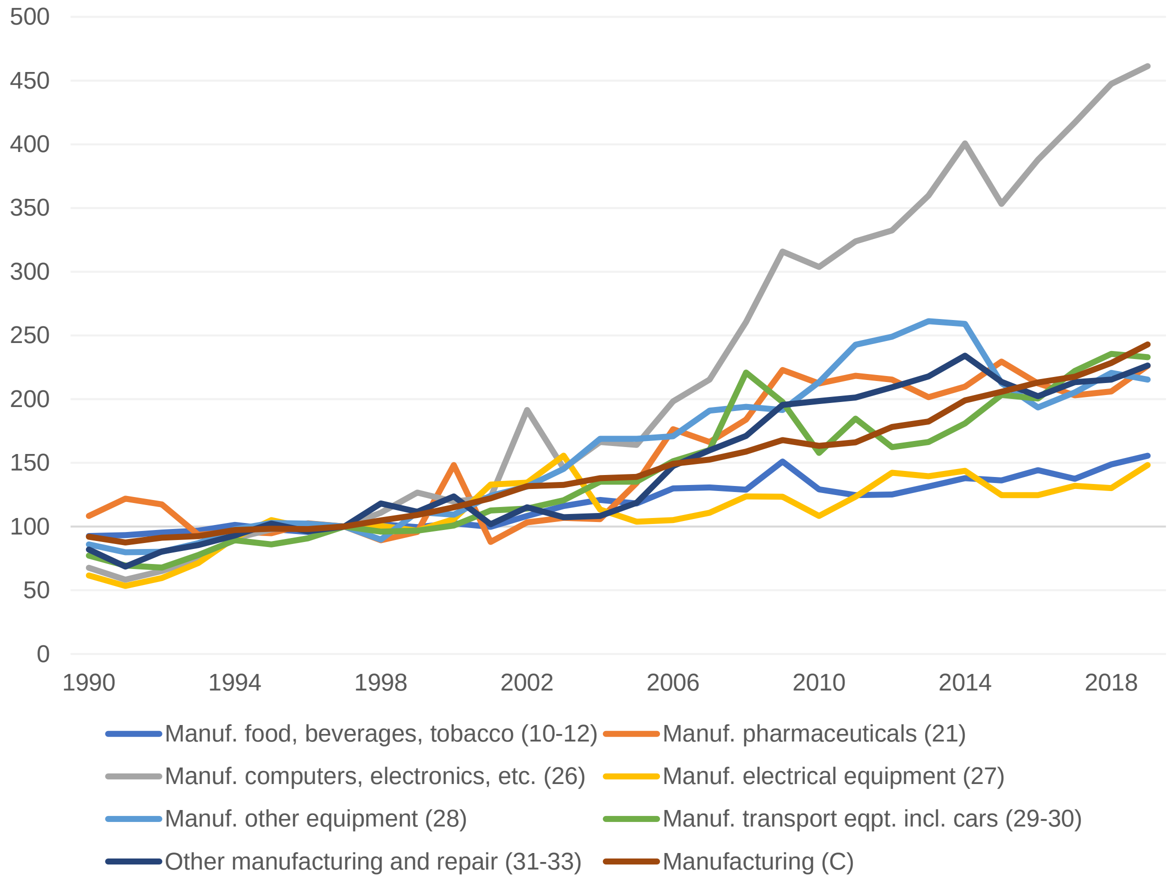
Annex B – energy-productivity, by industry, time series charts, 1990 to 2019

Energy-productivity, chained volume measures, index 1997 = 100.

SIC 2007 industry sections and divisions given in parentheses.



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Manuf. transport eqpt. incl. cars (29-30)
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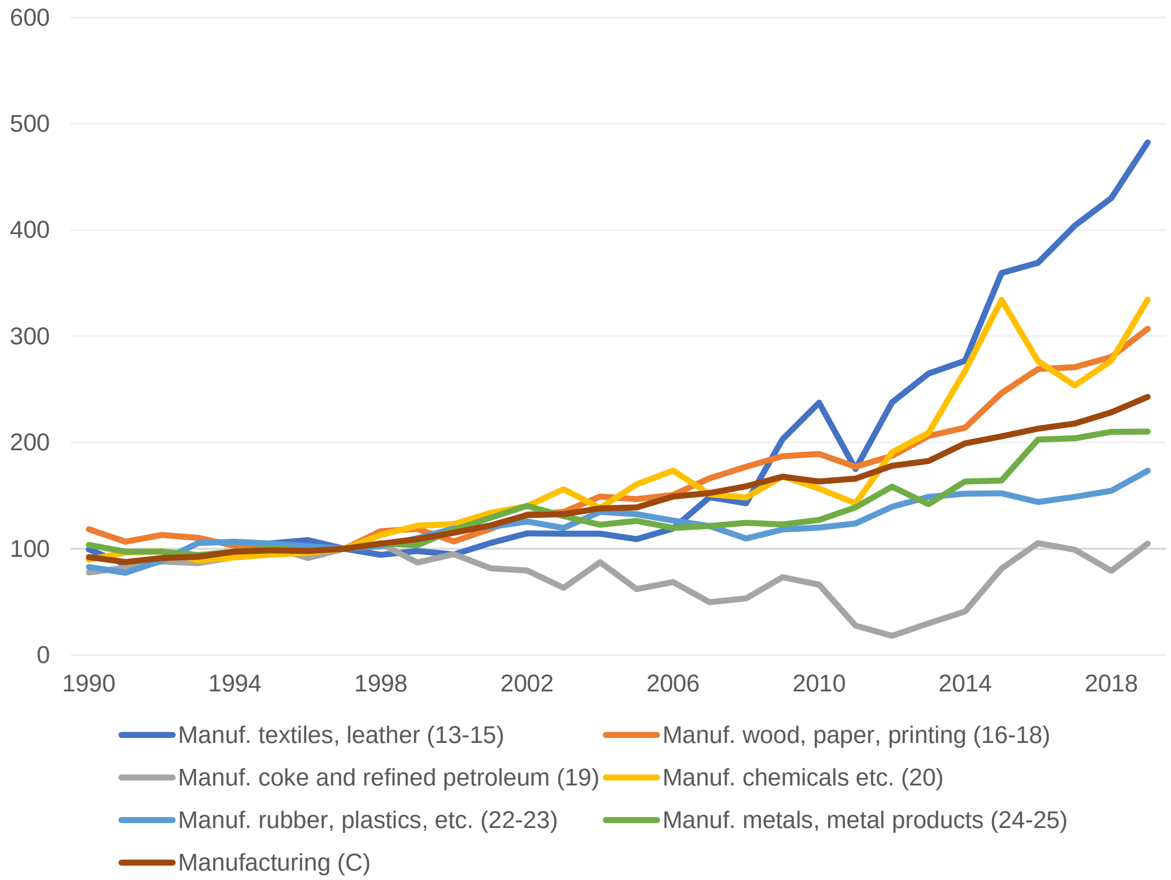
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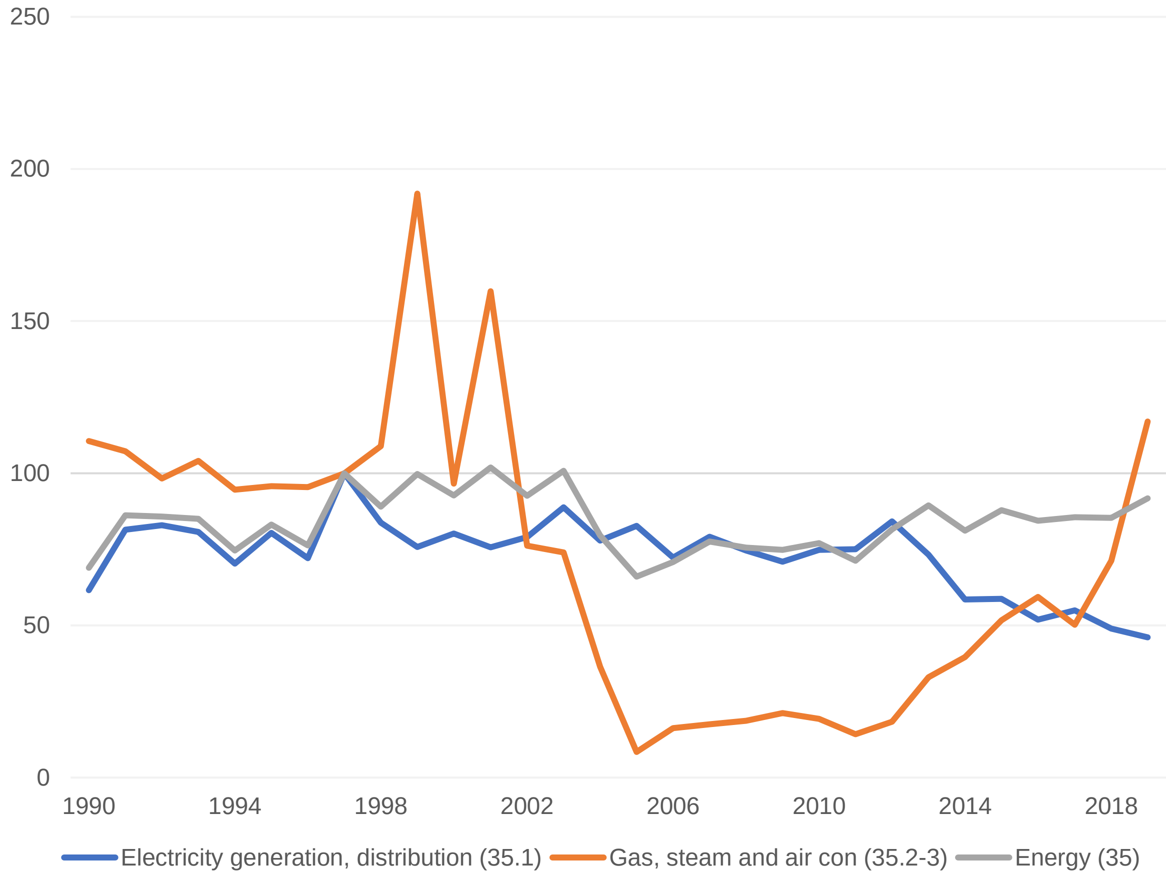
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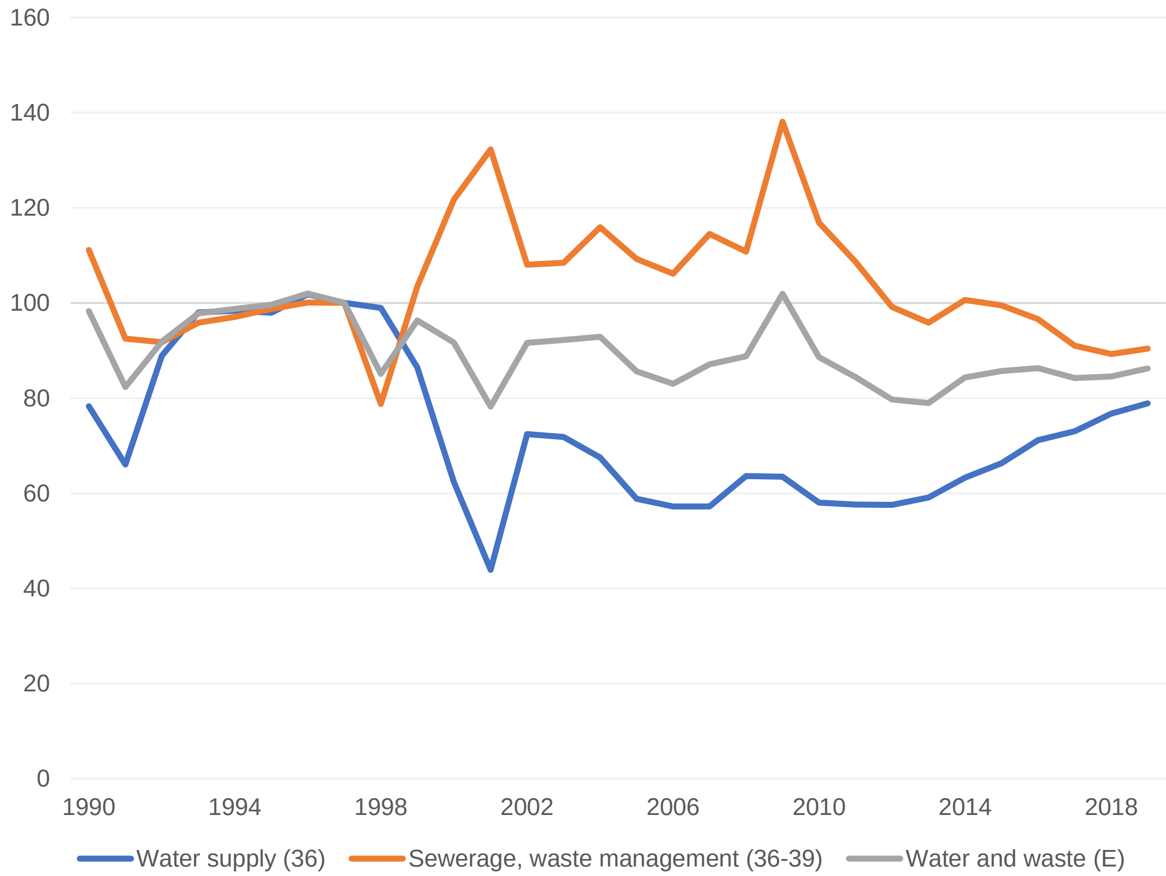
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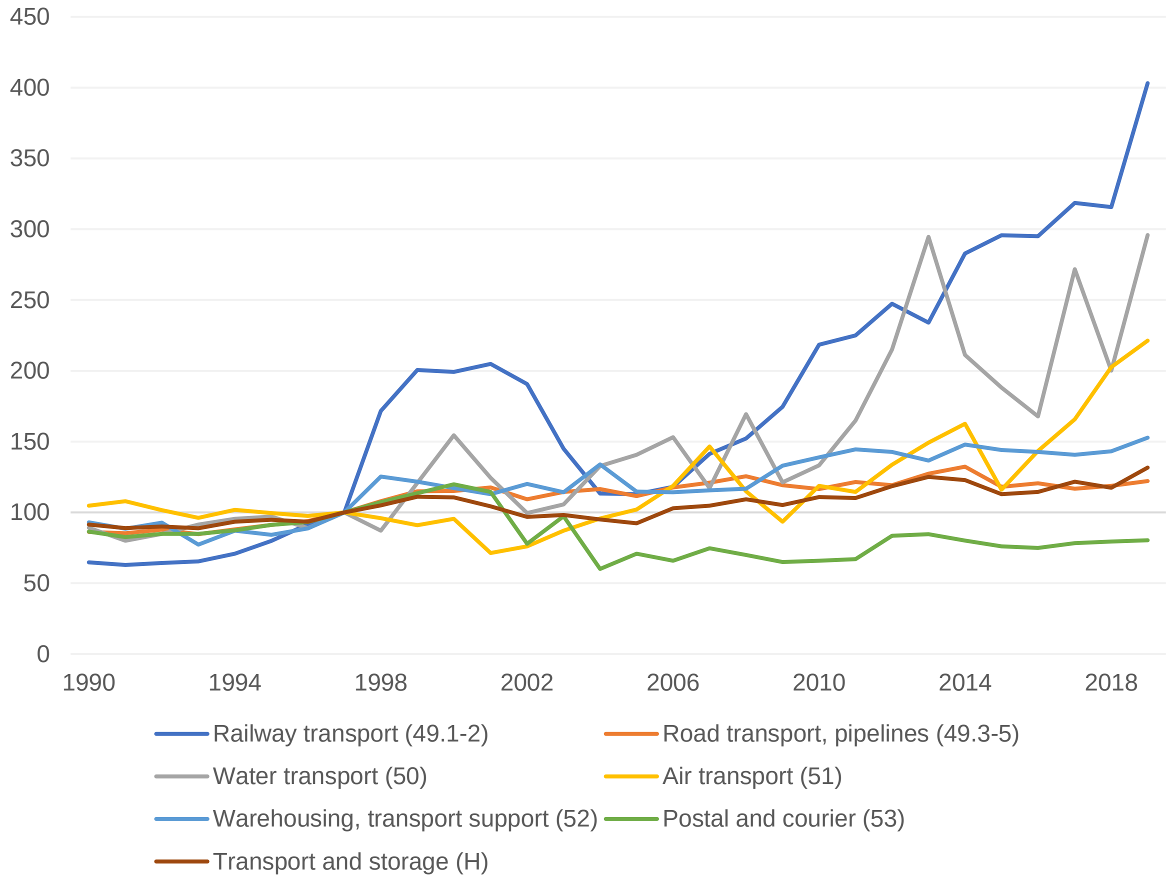
Water and waste (E)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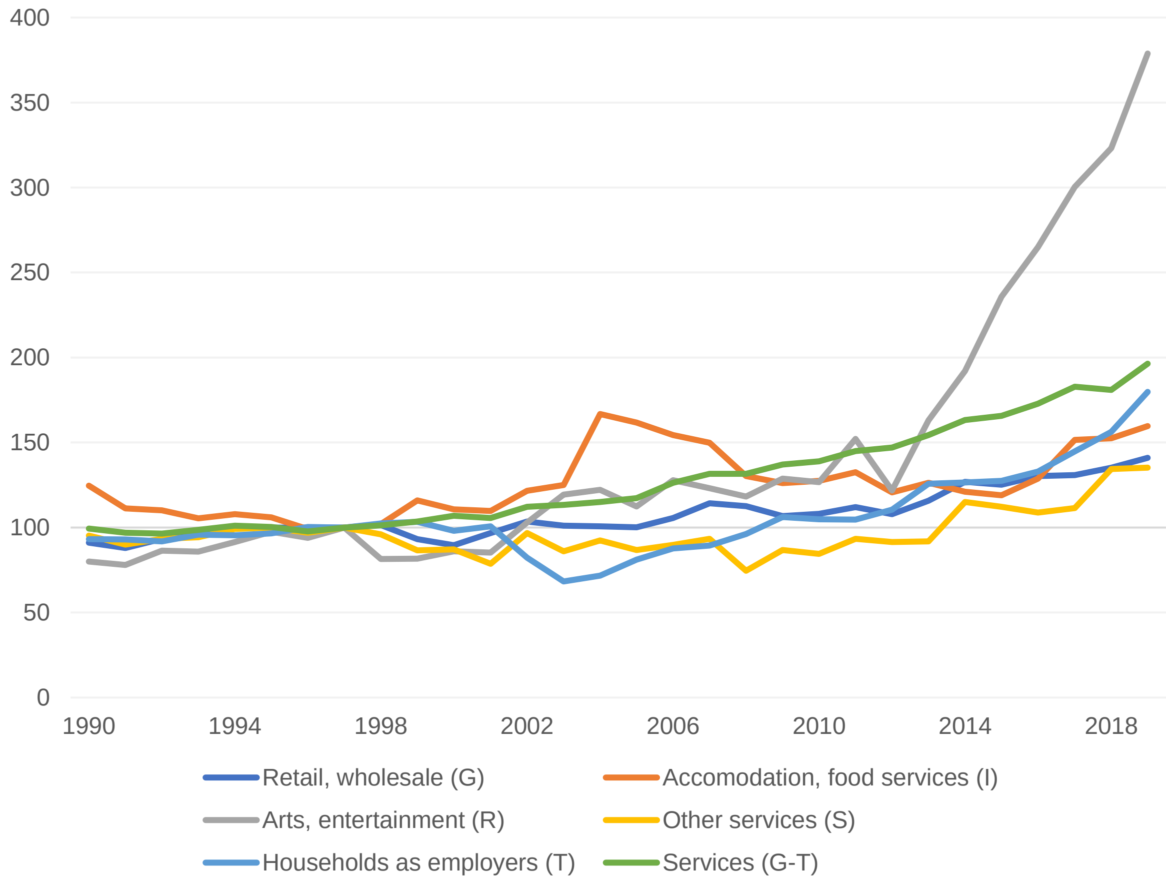
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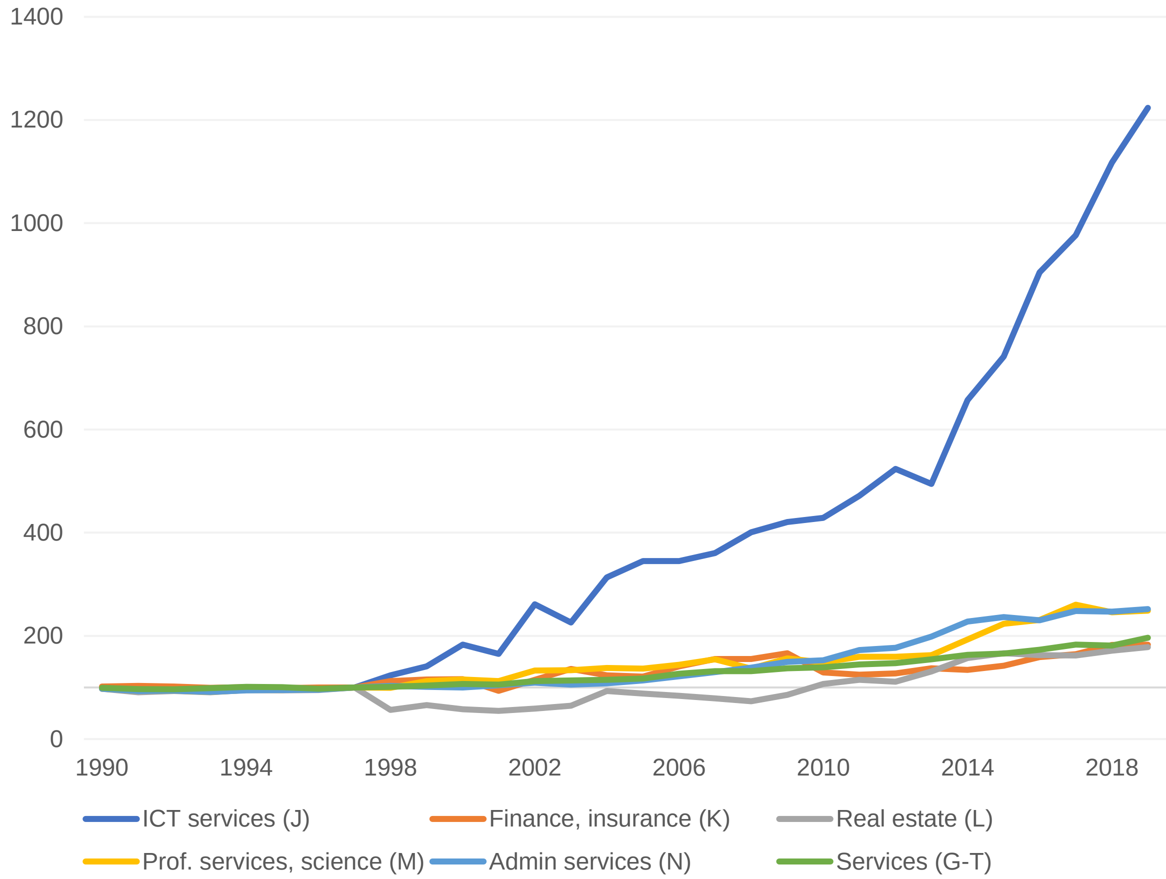
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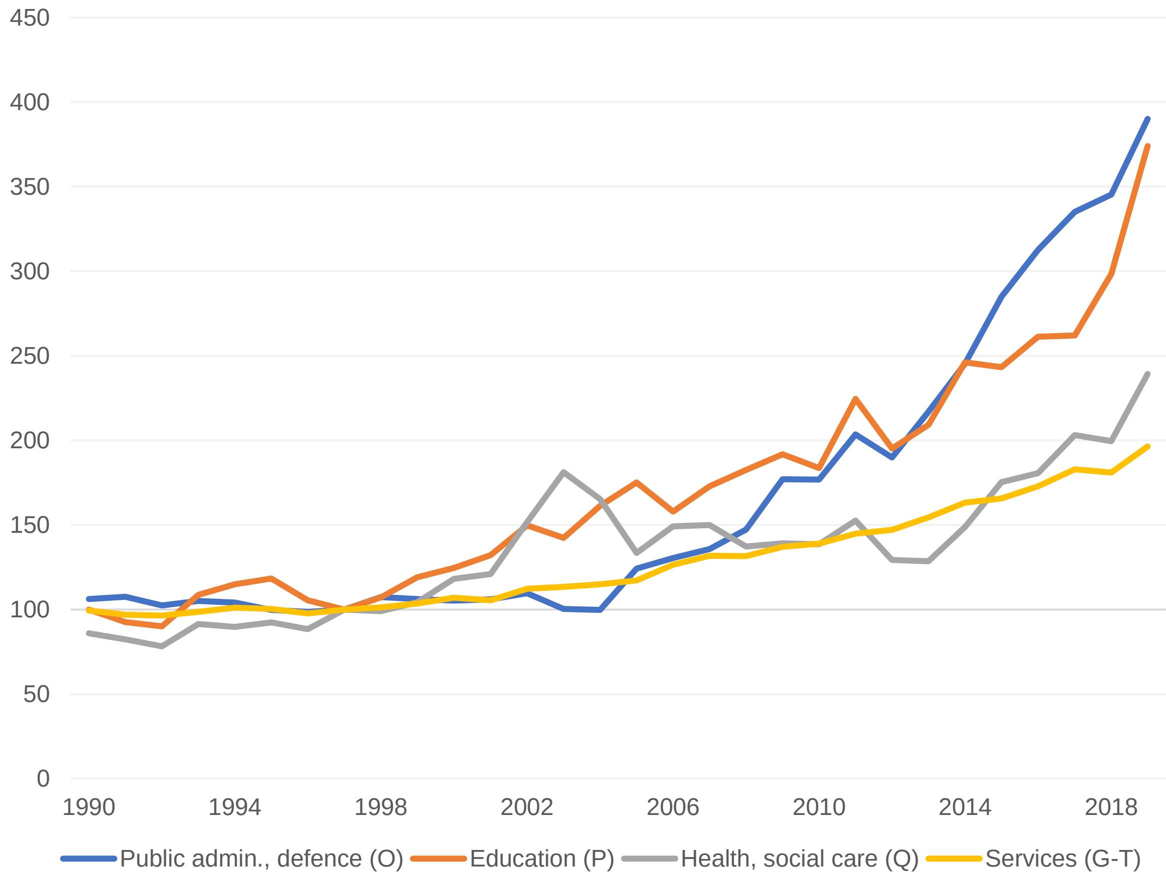
Admin services (N)
Services (G-T)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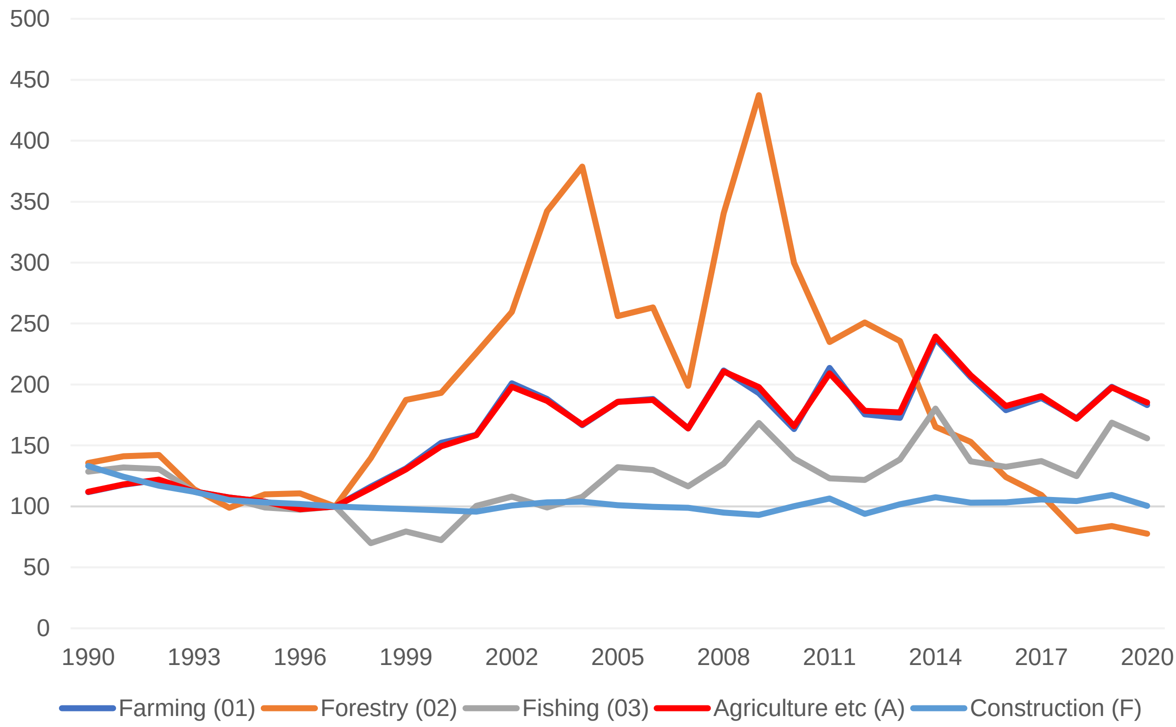
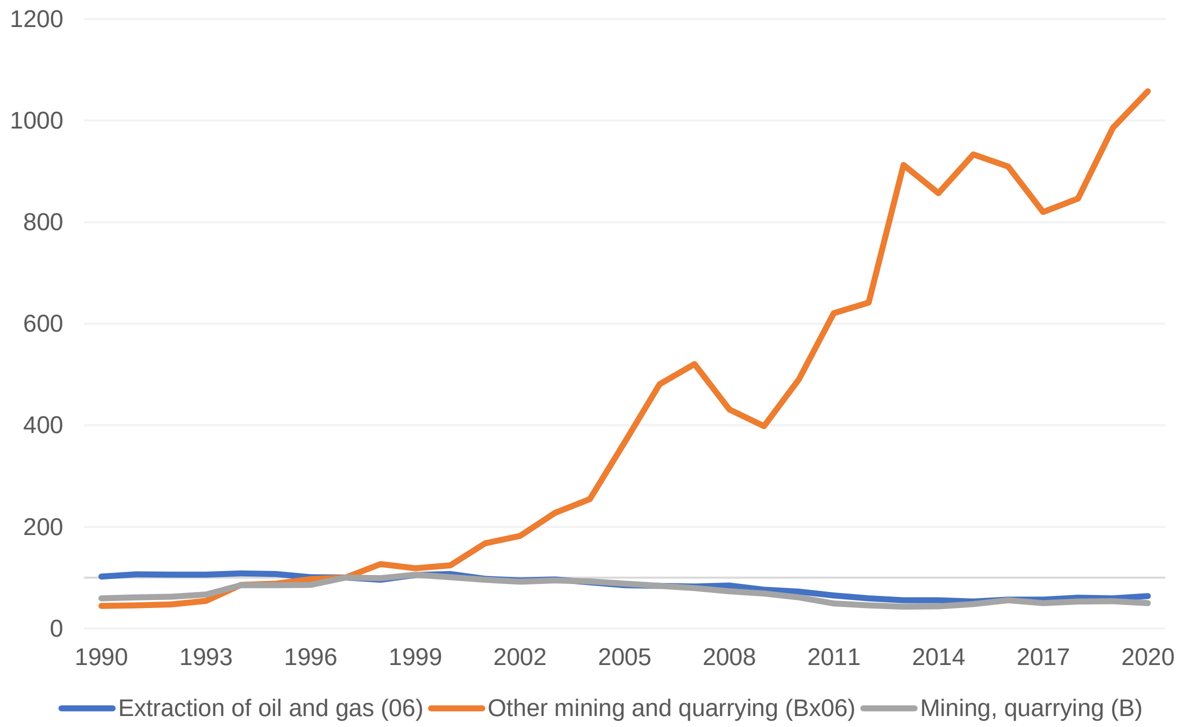
Education (P)
Health, social care (Q)
Services (G-T)

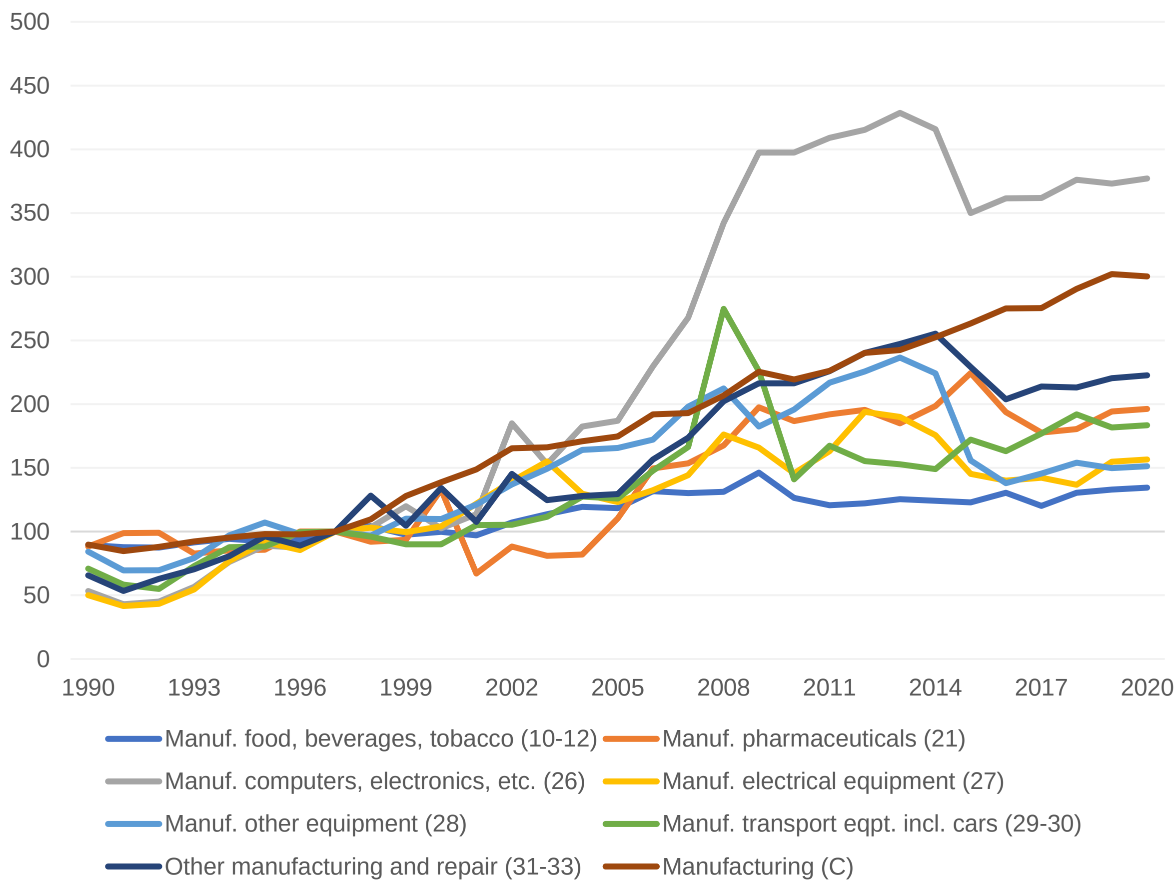
Annex C – emissions-productivity, by industry, time series charts, 1990 to 2020

Emissions-productivity, chained volume measures, index 1997 = 100.

SIC 2007 industry sections and divisions given in parentheses.



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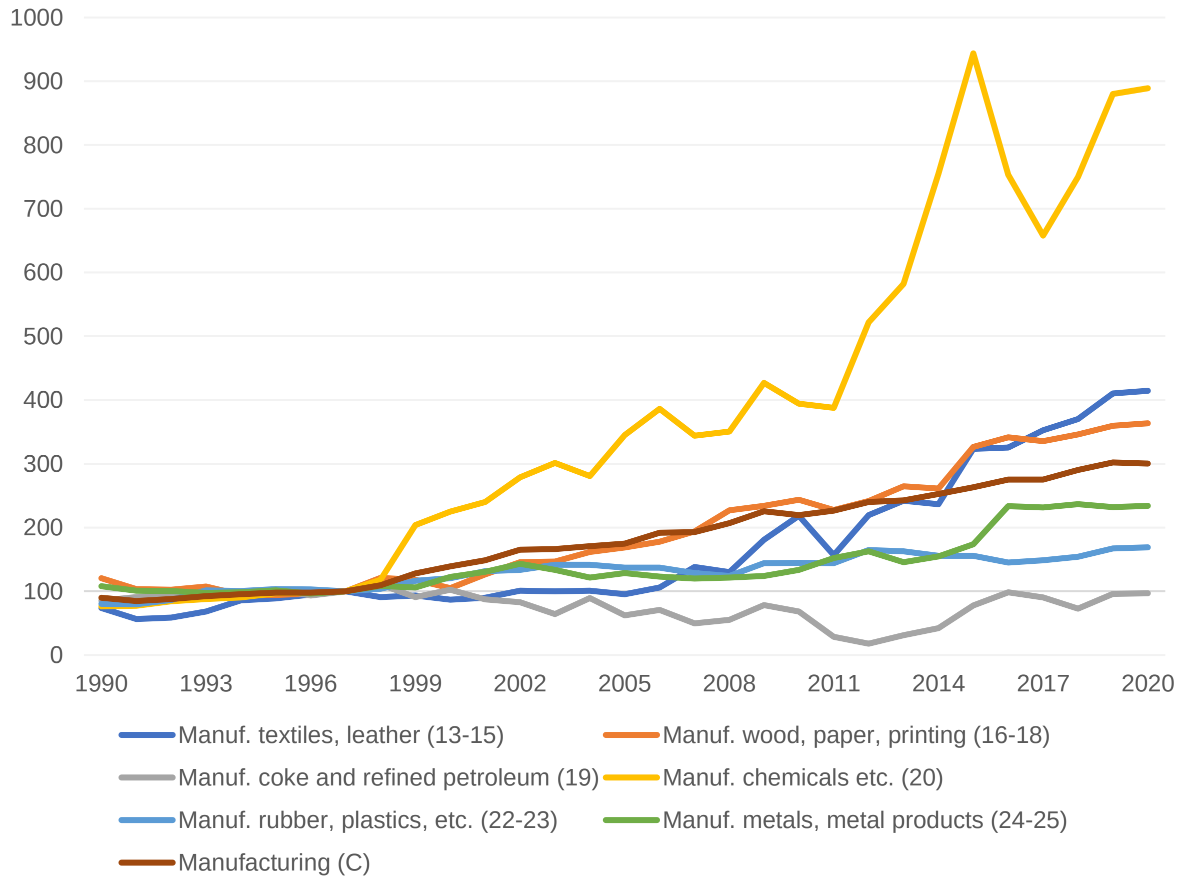
Other manufacturing and repair (31-33)
Manufacturing (C)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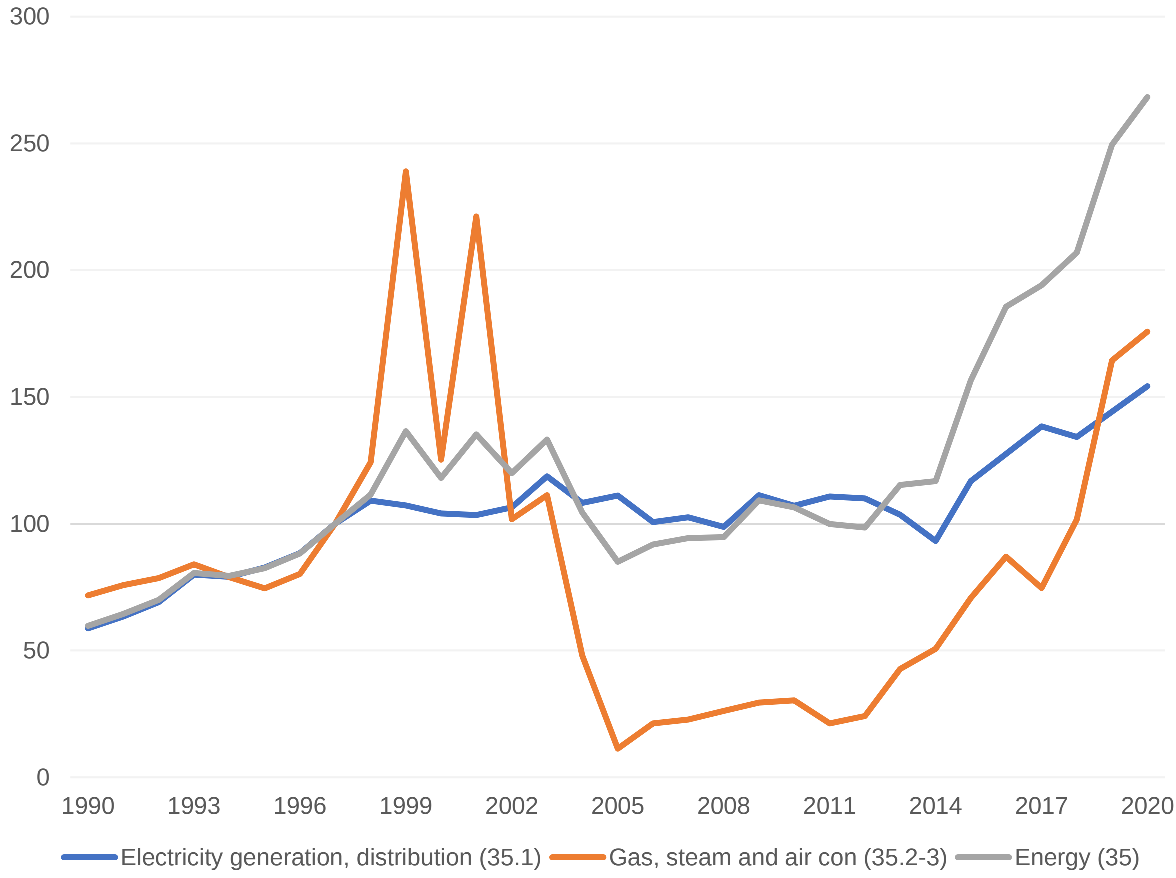
Manuf. metals, metal products (24-25)
Manufacturing (C)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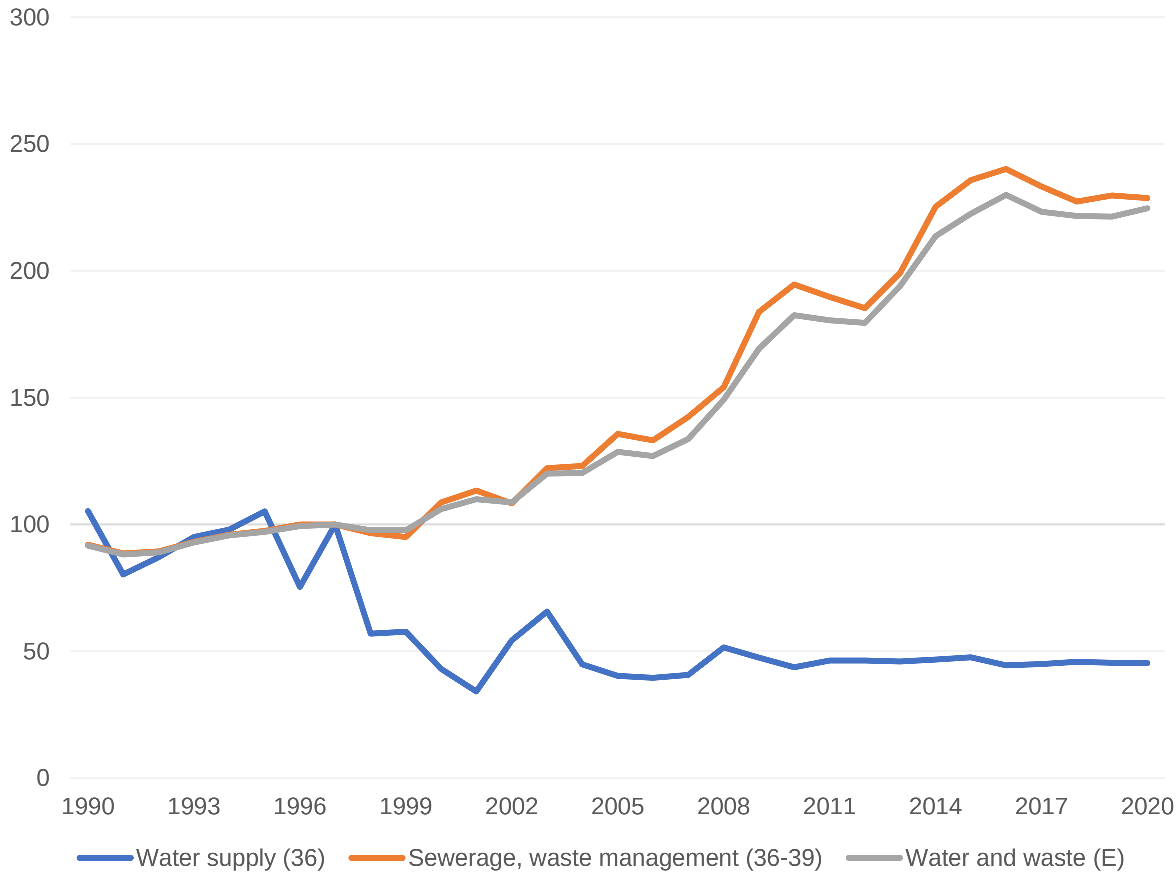
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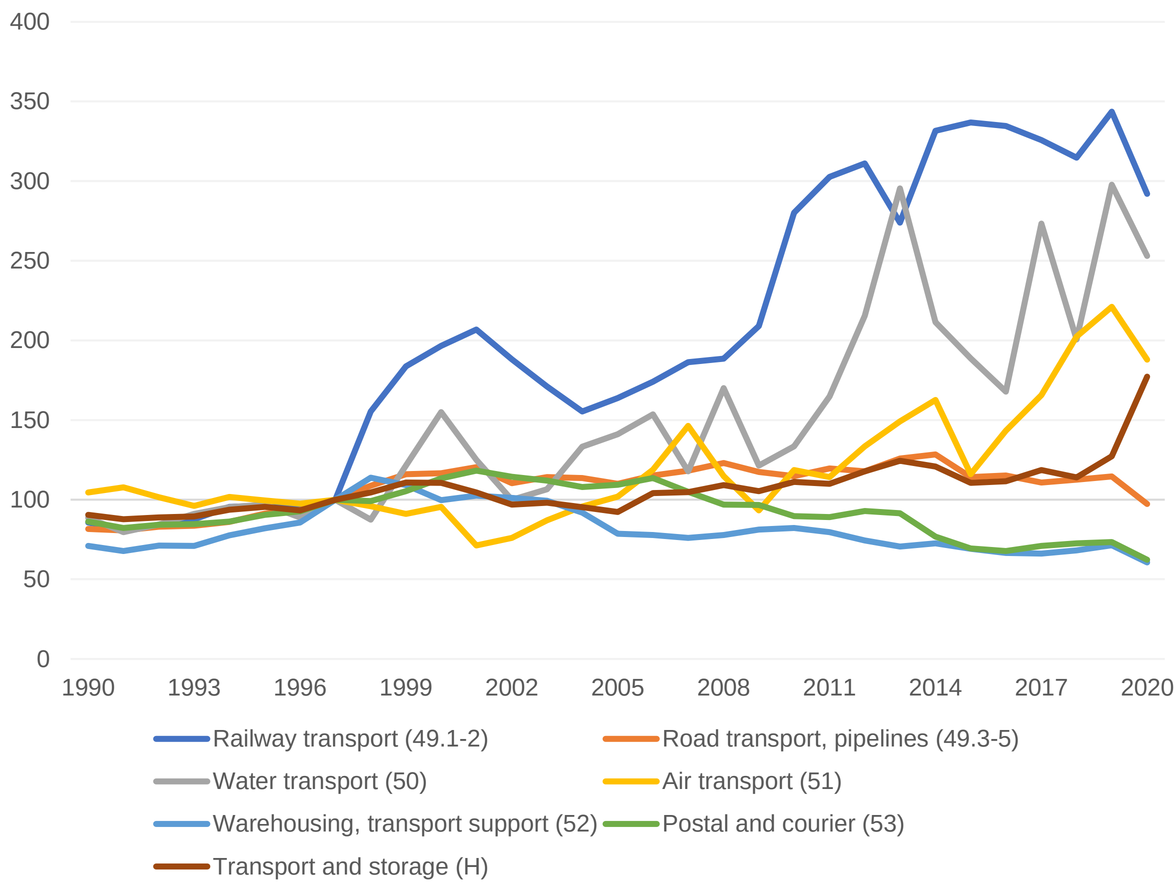
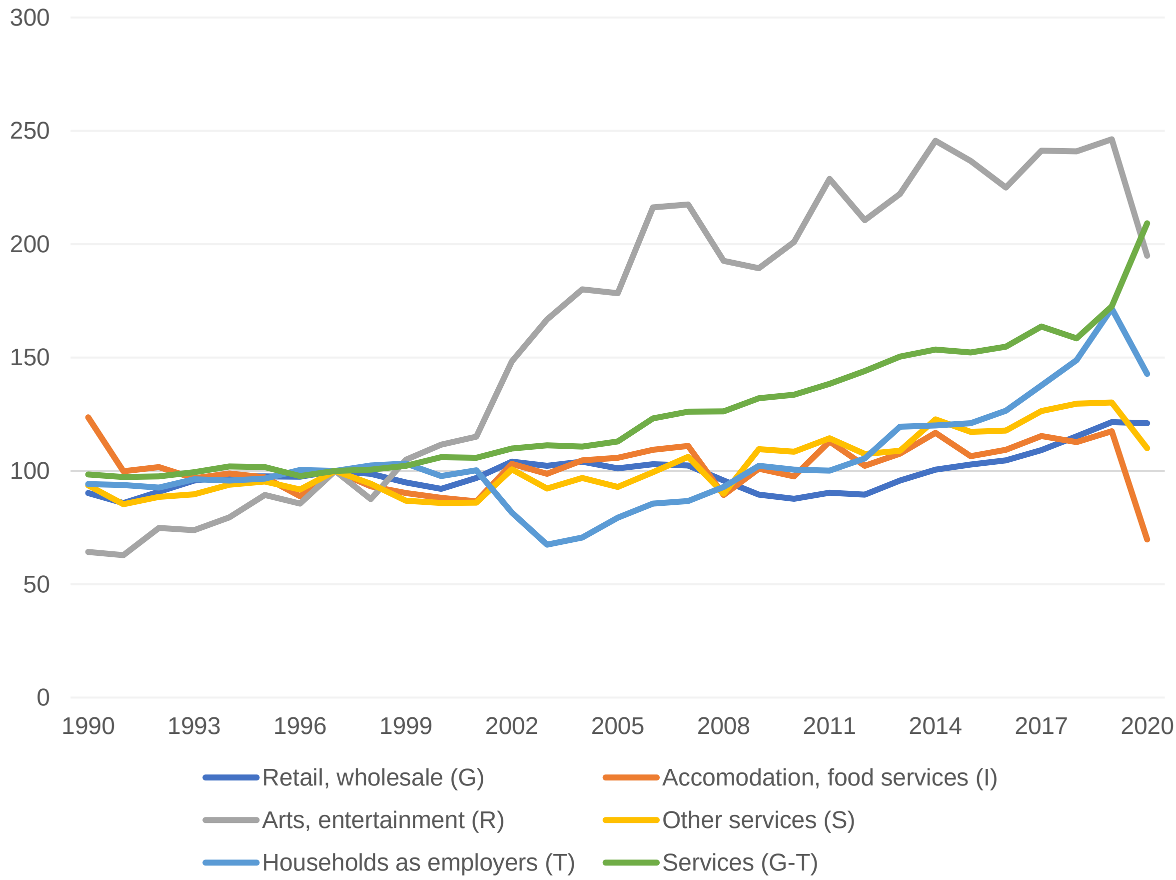
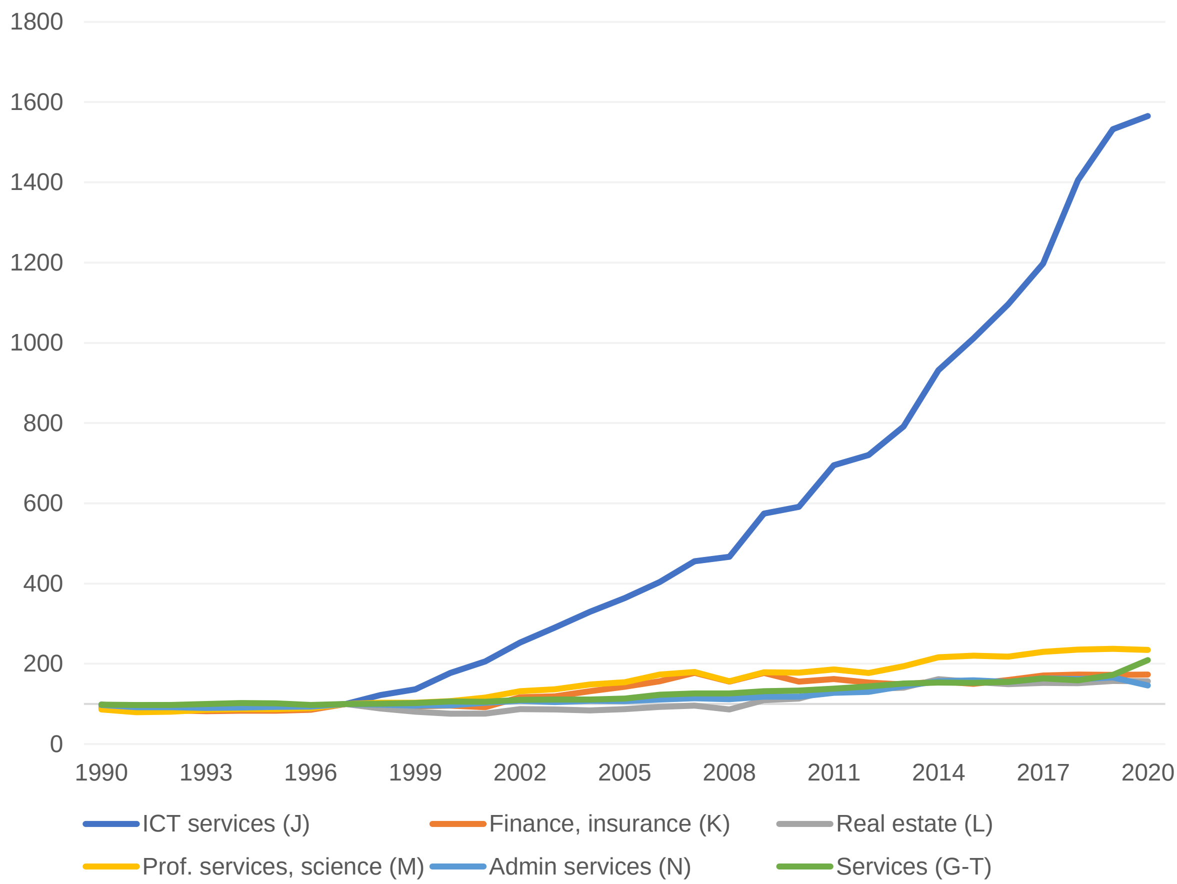
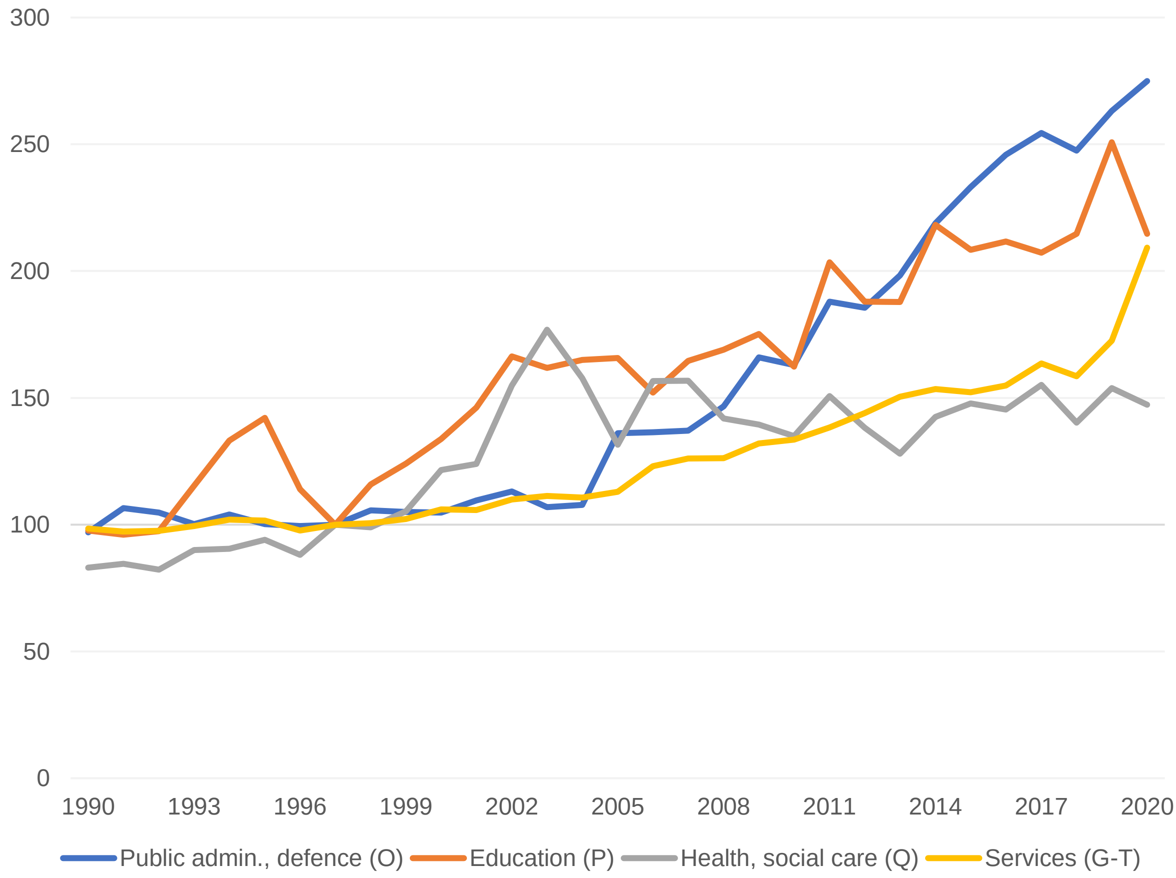
Sewerage, waste management (36-39)
Water and waste (E)


400
350
300
250
200
150
100
50
0
1990
1993
1996
1999
2002
2005
2008
2011
2014
2017
2020
Railway transport (49.1-2)
Road transport, pipelines (49.3-5)
Water transport (50)
Air transport (51)
Warehousing, transport support (52)
Postal and courier (53)
Transport and storage (H)


300
250
200
150
100
50
0
1990
1993
1996
1999
2002
2005
2008
2011
2014
2017
2020
Retail, wholesale (G)
Accomodation, food services (I)
Arts, entertainment (R)
Other services (S)
Households as employers (T)
Services (G-T)


1800
1600
1400
1200
1000
800
600
400
200
0
1990 1993 1996 1999 2002 2005 2008 2011 2014 2017 2020
ICT services (J)
Finance, insurance (K)
Real estate (L)
Prof. services, science (M)
Admin services (N)
Services (G-T)


300
250
200
150
100
50
0
1990 1993 1996 1999 2002 2005 2008 2011 2014 2017 2020
Public admin., defence (O)
Education (P)
Health, social care (Q)
Services (G-T)

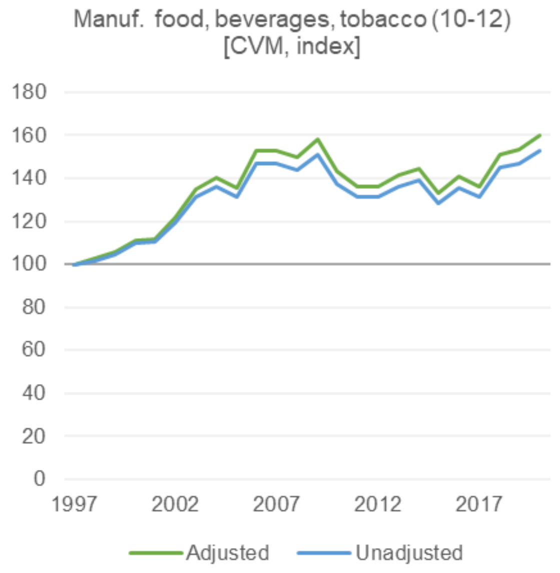
Annex D – labour productivity with bad outputs, by industry, time series charts, 1997 to 2020

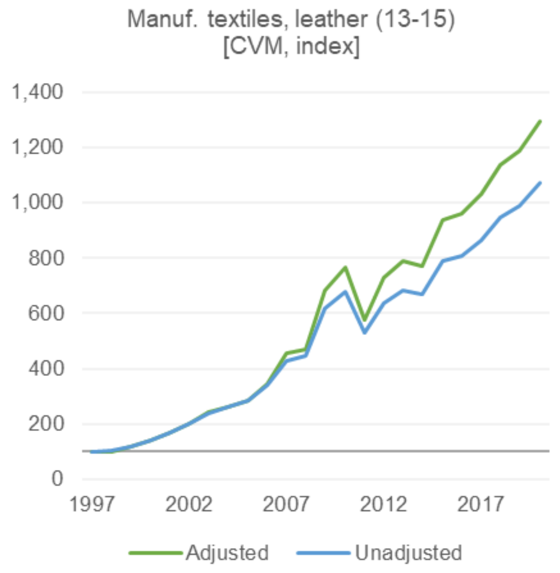
Labour productivity with bad outputs, chained volume measures, index 1997 = 100.

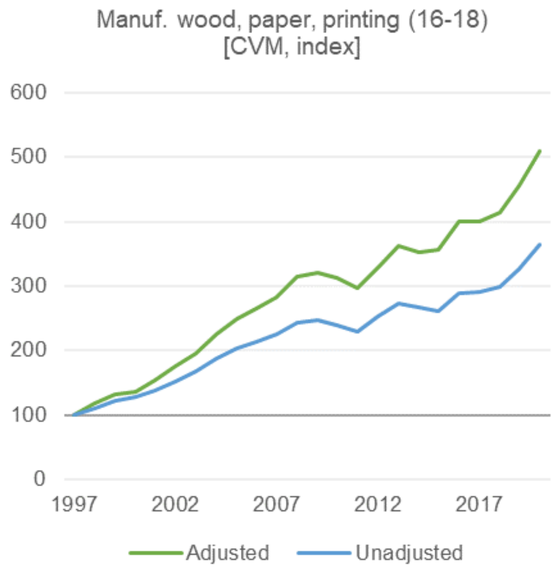
Selected industries are shown in text, and are not repeated here. Some industries see negative (or very low) GVA after adjusting for bad outputs, which makes it difficult to calculate CVMs and construct indexes. These are instead shown in current prices. Scales vary between charts.

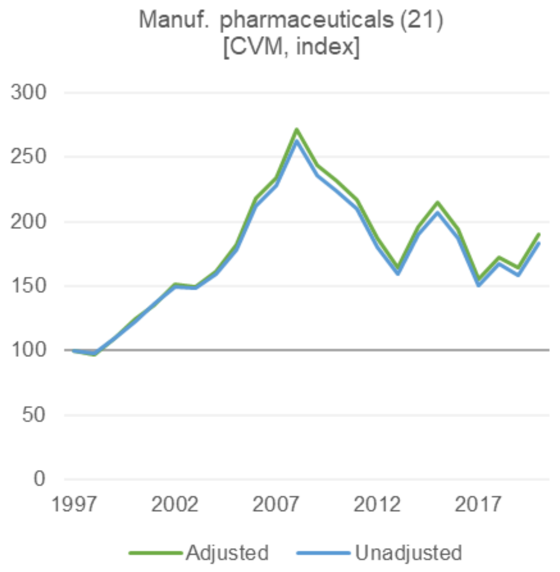
SIC 2007 industry sections and divisions given in parentheses.

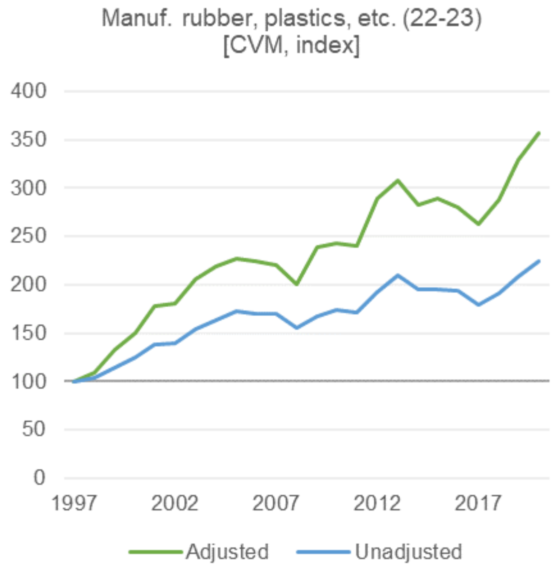
<u>Industries with positive GVA (and no chaining issues) after adjusting for bad outputs, shown in CVM indices</u>

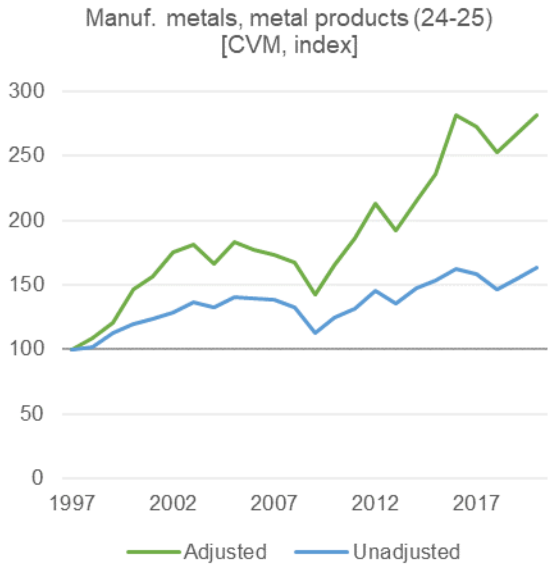


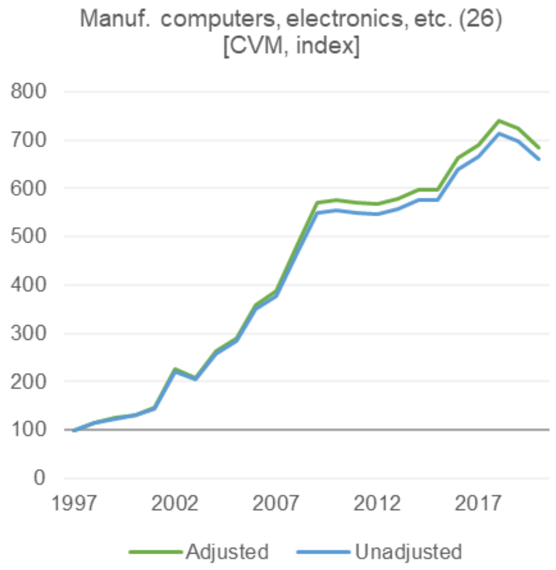




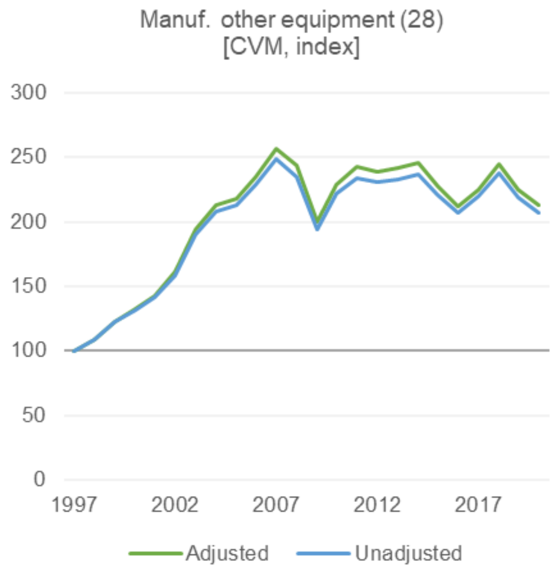


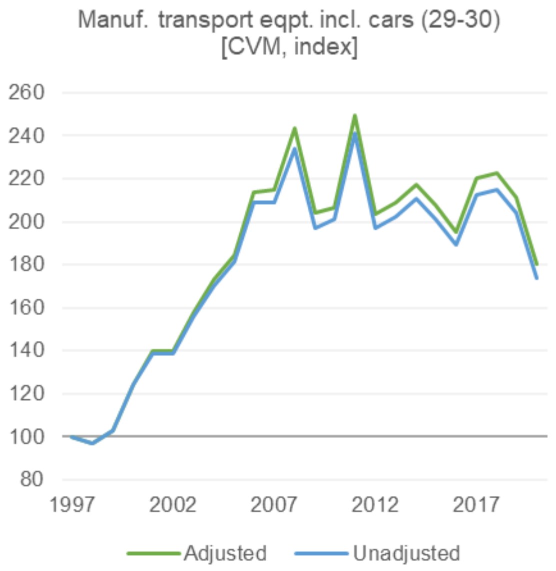

Manuf. rubber, plastics, etc. (22-23)
[CVM, index]
400
350
300
250
200
150
100
50
0
1997
2002
2007
2012
2017
Adjusted
Unadjusted

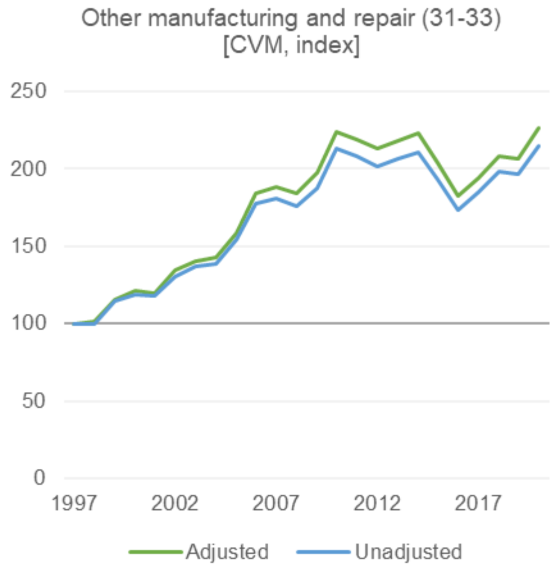

Manuf. metals, metal products (24-25)
[CVM, index]
300
250
200
150
100
50
0
1997
2002
2007
2012
2017
Adjusted
Unadjusted


Manuf. computers, electronics, etc. (26)
[CVM, index]
800
700
600
500
400
300
200
100
0
1997
2002
2007
2012
2017
Adjusted
Unadjusted

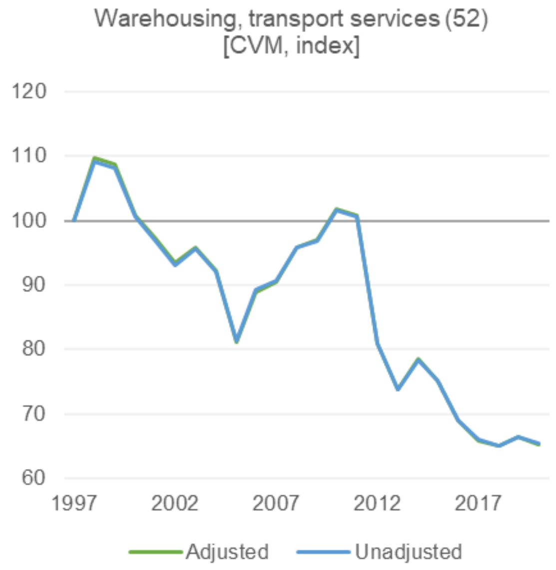

Manuf. electrical equipment (27)
[CVM, index]
300
250
200
150
100
50
0
1997
2002
2007
2012
2017
Adjusted
Unadjusted

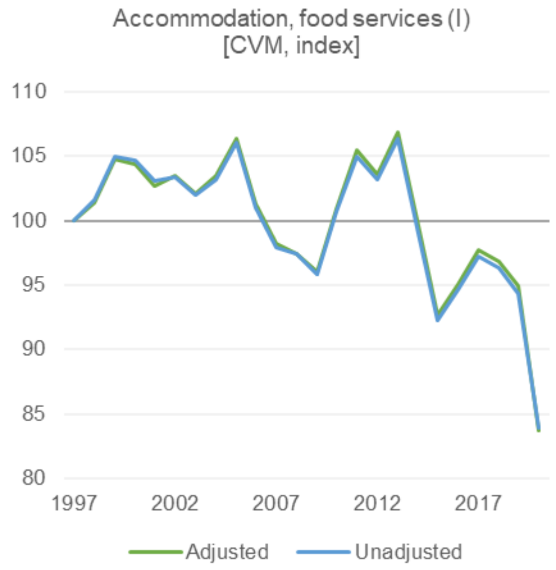

Manuf. other equipment (28)
[CVM, index]
300
250
200
150
100
50
0
1997
2002
2007
2012
2017
Adjusted
Unadjusted

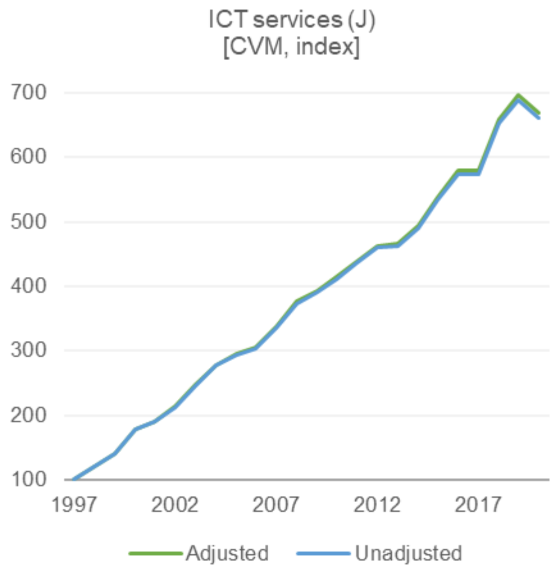

Manuf. transport eqpt. incl. cars (29-30)
[CVM, index]
260
240
220
200
180
160
140
120
100
80
1997
2002
2007
2012
2017
Adjusted
Unadjusted

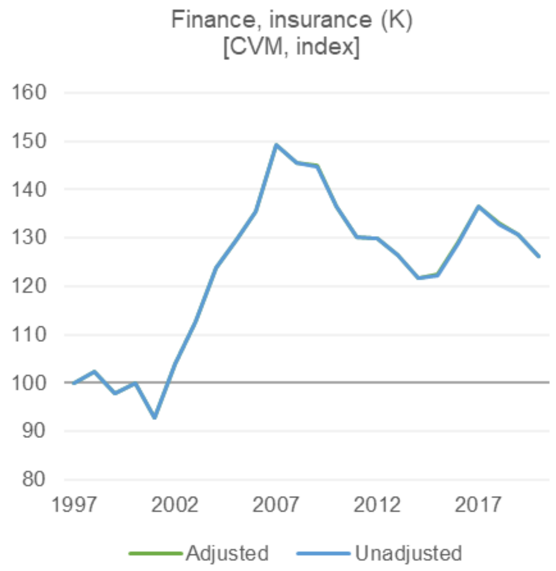

Other manufacturing and repair (31-33)
[CVM, index]
250
200
150
100
50
0
1997
2002
2007
2012
2017
Adjusted
Unadjusted


Retail, wholesale, motor trades (G)
[CVM, index]
125
120
115
110
105
100
95
90
85
80
1997
2002
2007
2012
2017
Adjusted
Unadjusted

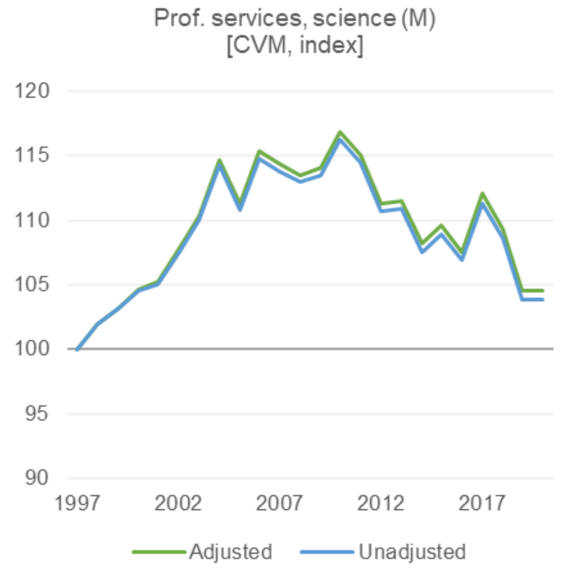

Warehousing, transport services (52)
[CVM, index]
120
110
100
90
80
70
60
1997
2002
2007
2012
2017
Adjusted
Unadjusted

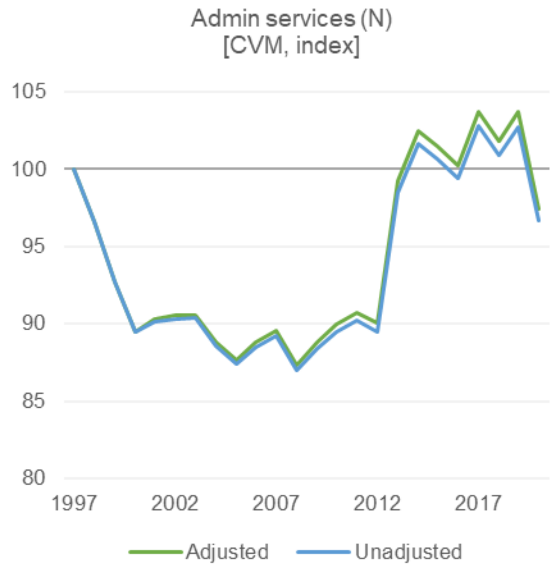

Accommodation, food services (I)
[CVM, index]
110
105
100
95
90
85
80
1997
2002
2007
2012
2017
Adjusted
Unadjusted

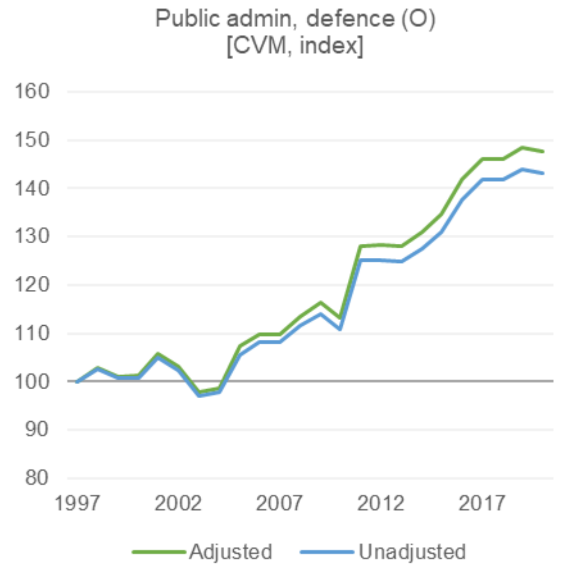

ICT services (J)
[CVM, index]
700
600
500
400
300
200
100
1997
2002
2007
2012
2017
Adjusted
Unadjusted

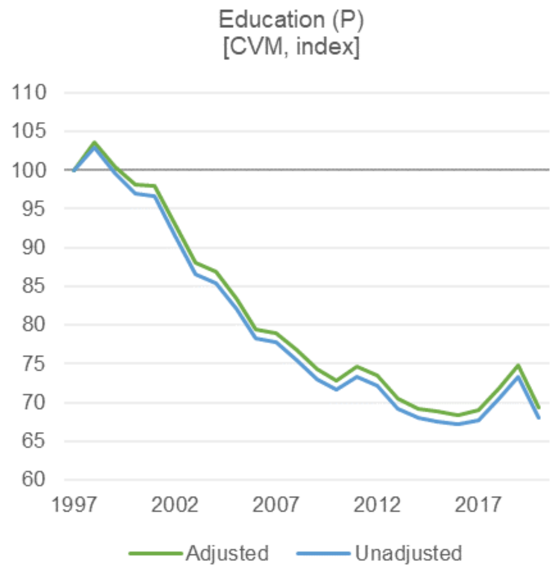

Finance, insurance (K)
[CVM, index]
160
150
140
130
120
110
100
90
80
1997
2002
2007
2012
2017
Adjusted
Unadjusted

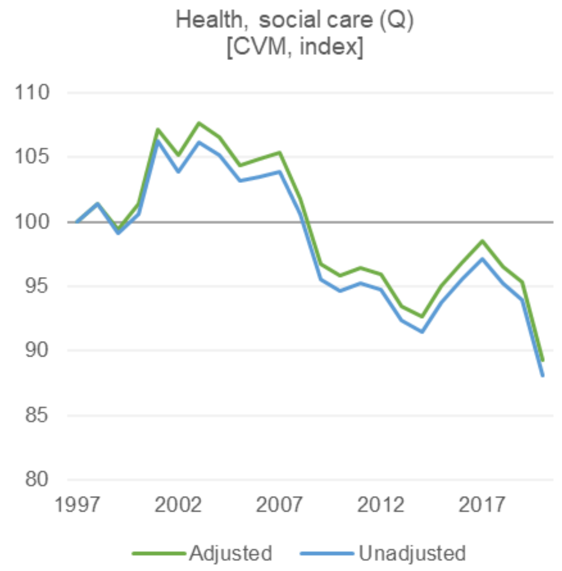

Real estate (L)
[CVM, index]
105
100
95
90
85
80
75
70
65
60
1997
2002
2007
2012
2017
Adjusted
Unadjusted

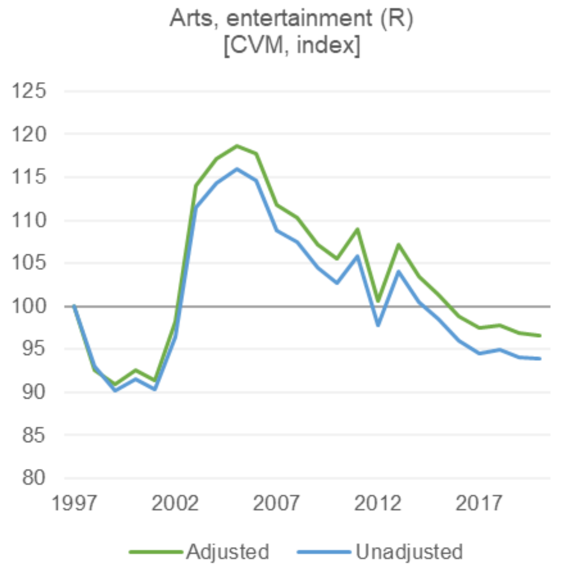

Prof. services, science (M)
[CVM, index]
120
115
110
105
100
95
90
1997
2002
2007
2012
2017
Adjusted
Unadjusted

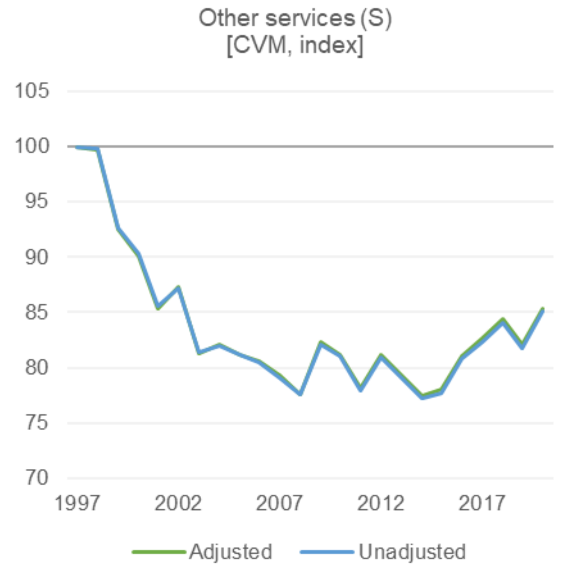

Admin services (N)
[CVM, index]
105
100
95
90
85
80
1997
2002
2007
2012
2017
Adjusted
Unadjusted


Public admin, defence (O)
[CVM, index]
160
150
140
130
120
110
100
90
80
1997
2002
2007
2012
2017
Adjusted
Unadjusted

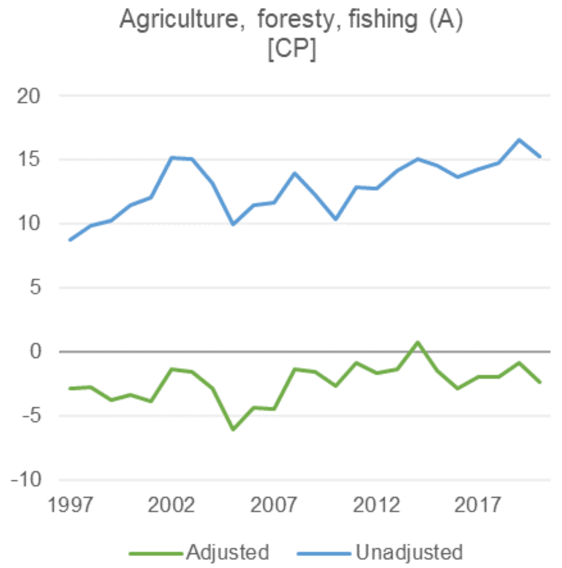

Education (P)
[CVM, index]
110
105
100
95
90
85
80
75
70
65
60
1997
2002
2007
2012
2017
Adjusted
Unadjusted

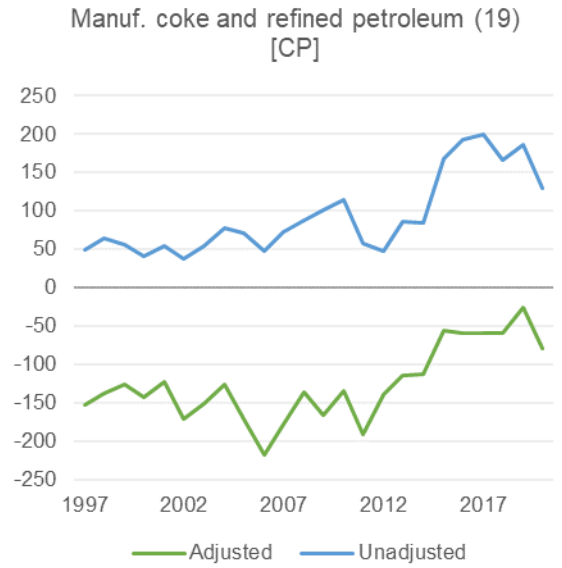

Health, social care (Q)
[CVM, index]
110
105
100
95
90
85
80
1997
2002
2007
2012
2017
Adjusted
Unadjusted

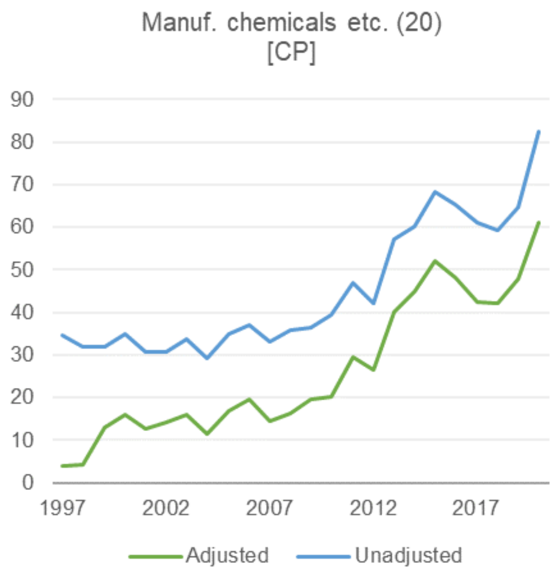


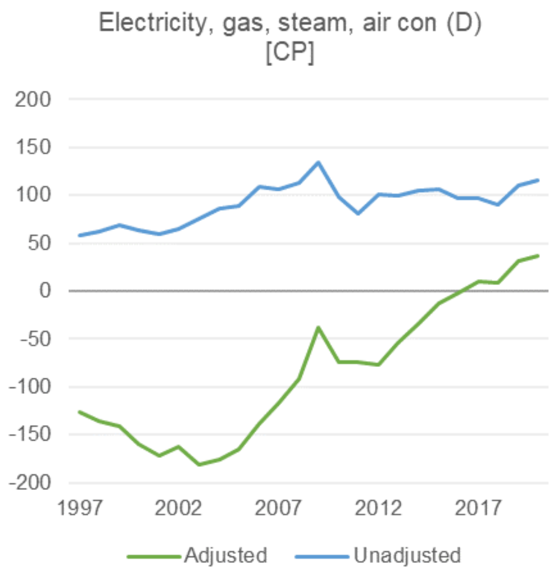


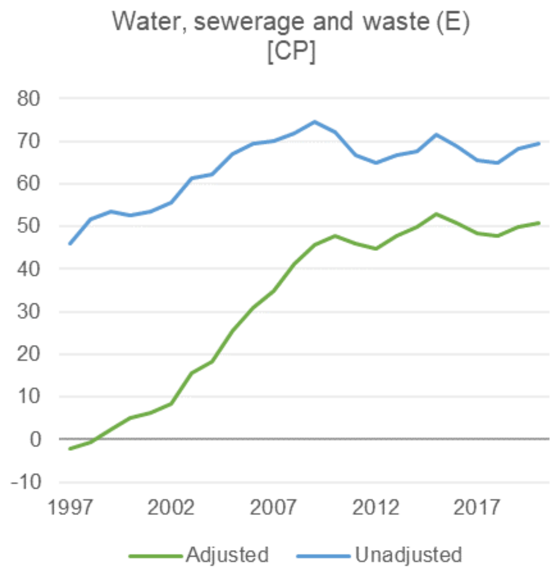
<u>Industries with negative GVA (or chaining issues) after adjusting for bad outputs, shown in current prices</u>

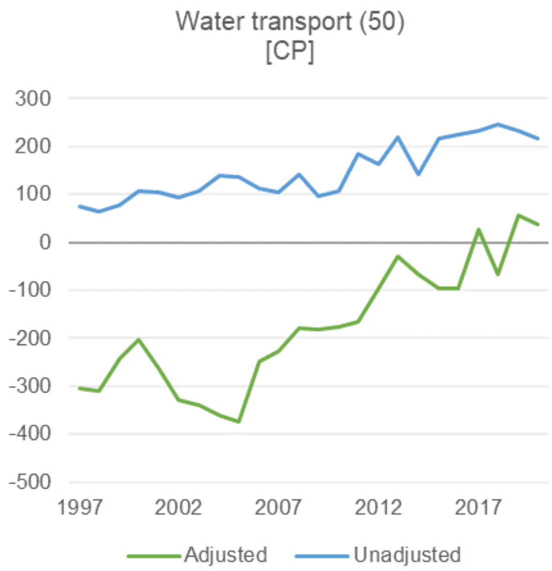


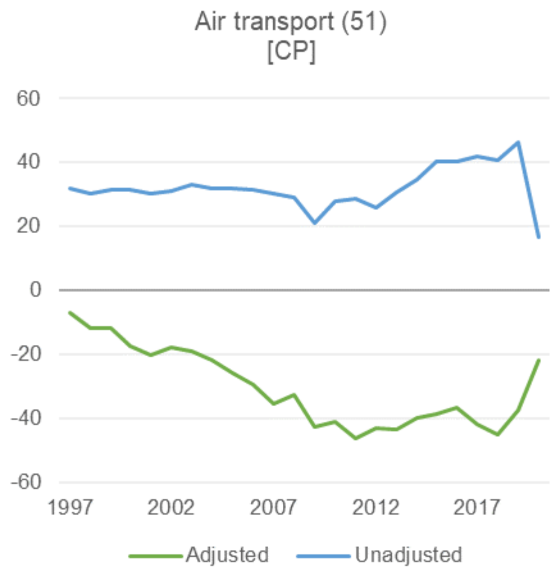



Manuf. chemicals etc. (20)
[CP]
90
80
70
60
50
40
30
20
10
0
1997
2002
2007
2012
2017
Adjusted
Unadjusted


Electricity, gas, steam, air con (D)
[CP]
200
150
100
50
0
-50
-100
-150
-200
1997
2002
2007
2012
2017
Adjusted
Unadjusted


Water, sewerage and waste (E)
[CP]
80
70
60
50
40
30
20
10
0
-10
1997
2002
2007
2012
2017
Adjusted
Unadjusted


Water transport (50)
[CP]
300
200
100
0
-100
-200
-300
-400
-500
1997
2002
2007
2012
2017
Adjusted
Unadjusted


Air transport (51)
[CP]
60
40
20
0
-20
-40
-60
1997
2002
2007
2012
2017
Adjusted
Unadjusted

Annex E – details of the method to estimate unmeasured environmental protection output

A summary of the method to estimate unmeasured environmental output is given in the main text. This Annex provides additional details.

Summary of Martin and Monahan (2022)

Martin and Monahan (2022a) details the method, and Martin and Monahan (2022b) shows results of that method. The following brief summary is copied directly from Martin and Monahan (2022b, section 9).

"Time spent on green tasks is estimated using task-level data available in the US O*NET database. No equivalent database exists for the UK.

O*NET has, for each of almost 1000 detailed occupations, a list of around 20 occupation-specific tasks. For each task, data on the frequency of the task, the importance and relevance of the task, and other data, is collected from workers doing that occupation or occupational experts. These data are updated periodically for each occupation.

We use the information on the relevance and frequency of each task, combined with a marker for which tasks are green to estimate the fraction of time spent on green tasks. These are identified in the O*NET database between 2011 and 2019 based on a 2011 study. We add these markers to earlier and later releases of the O*NET database using automated and manual processes.

To fill in the gaps between data collections, we use linear interpolation and extrapolation to create estimates of the time spent on green tasks by occupation between 1997 and 2021. We then convert this from O*NET occupation codes to the UK Standard Occupation Classification (UK SOC), via the US Standard Occupation Classification (US SOC), and the International Standard Classification of Occupations (ISCO). Given the majority of matches are not one-to-one, we take the arithmetic average (mean) of converted green time shares by UK SOC code.

We then apply these green task time shares to UK labour market data."

Non-labour cost uplifts

The non-labour cost uplifts account for all costs other than wages and salaries, namely: non-wage labour costs (such as pension contributions and employers' National Insurance contributions), materials, overheads, cost of using capital assets (such as buildings, machinery, computers and software), and a mark-up for net operating surplus (a profit market). The inclusion of a profit margin put the estimate on an equivalent footing to market output, and is in line with national accounting guidance.

The mark-up for non-wage labour costs is assumed at 20% for all occupations in all years. The other cost uplift factors vary by occupation, reflecting the different types of environmental protection output those different occupations do. Occupations are matched to industries whose cost structures are thought to be representative of the cost structures of the relevant environmental protection output. The correspondence between SOC 2010 codes and industries used for the cost uplift factors are given in Table E1.

Table E1 – Industries used for cost uplift factors

Industry cost structure	**Occupation types (SOC 2010)**	**Number of SOC 2010 codes matched**
70	Managerial, consultancy, business analysts, etc. (Major Groups 1, 2, 3)	42
71	Scientists, technical, engineers, etc. (Major Group 2, 3)	24
C	Manual – manufacturing (Major Groups 5, 8, 9)	23
F	Manual – construction (Major Groups 5, 8)	15
72	Researchers (Major Groups 2, 3)	10
H	Manual – transport (Major Groups 8, 9)	8
84	Civil servants (Major Groups 3, 4)	7
82	Administrative occupations (Major Groups 4, 7)	7
69	Legal professionals (Unit Groups 2412, 2419)	2
45	Vehicle technicians (Unit Groups 5231, 5232)	2
5	Mining operatives (Unit Groups 8122, 8123)	2
36	Manual – water and sewerage (Unit Group 8126)	1
38	Bin collectors (Unit Group 9235)	1
85	Vocational and industrial trainers (Unit Group 3563)	1

Notes: Major Groups are the highest of four levels of SOC 2010; Unit Groups are the lowest level.

The calculations use data from the ONS Supply and Use tables. We assume that only 50% of the intermediate consumption in each industry is relevant. So the cost uplift reflects:

- Mark-up from wages and salaries to compensation of employees = 20% for all occupations in all years
- Mark-up for intermediate consumption = varies by occupation, based on various industries, using only 50% of intermediate consumption of each industry
- Mark-up for use of capital and net operating surplus = varies by occupation, based on various industries

Adjustment for double counting

Section 7.1 provides considerable detail of the adjustments for double counting. Here we provide a few extra details.

For the R&D adjustment, Table E2 shows for the relevant R&D product groups the assumed proportion that relates to environmental protection, and is thus excluded to avoid double counting.

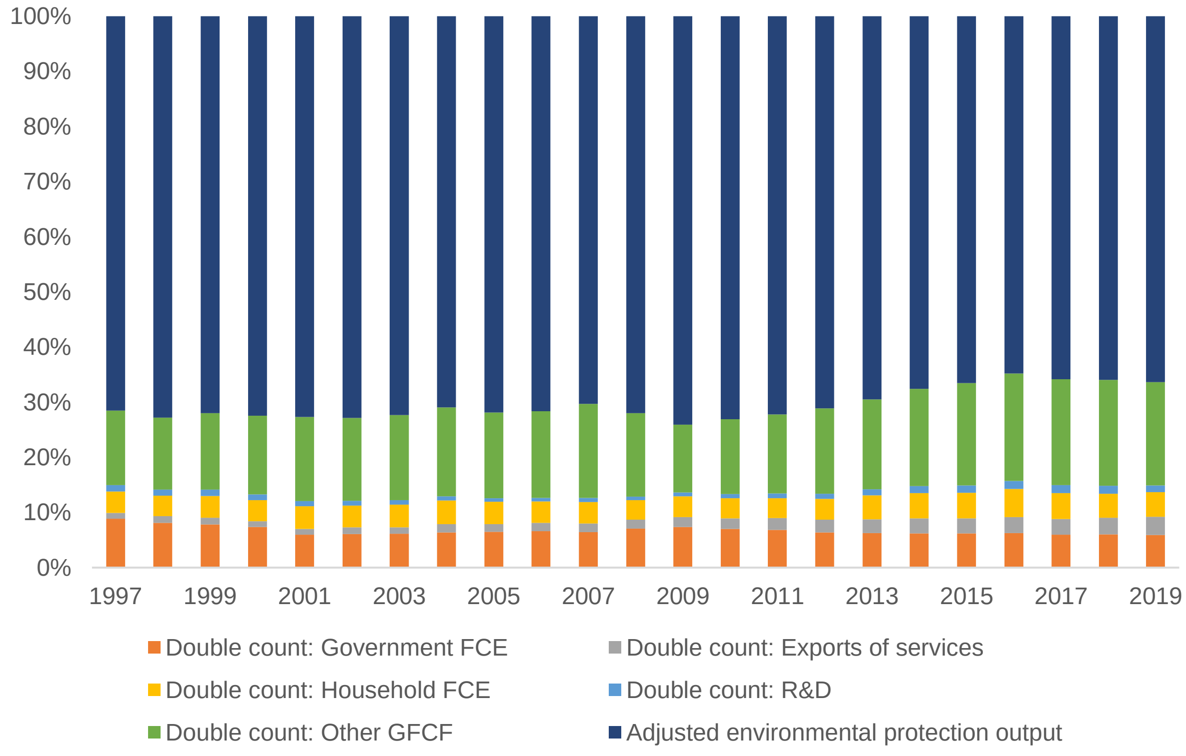
Figure E1 shows the proportions of total estimated environmental protection output removed to avoid double counting over time, by type of overlap.

Table E2 – Assumptions to estimate R&D double counting adjustment

R&D product group	Proportion assumed to overlap with environmental protection output
Sewerage, waste management & remediation	100%
Agriculture, hunting and forestry; Fishing	50%
Extractive Industries	50%
Refined Petrol/coke oven products	50%
Motor vehicles and parts	50%
Other transport equipment	50%
Electricity, gas and water supply	50%
Construction	50%
Transport & storage incl. postal/courier	50%
Miscellaneous business activities	10%

Notes: R&D product groups relate to the type of R&D, not the industry that is doing the investing. For instance, R&D into transport could be conducted by an airport, and would be recorded against the transport product group.

Figure E1 – Breakdown of total environmental protection output, by double counting adjustments and the adjusted output (excluding double counting)



Notes: FCE stands for "Final Consumption Expenditure"; GFCF stands for "Gross Fixed Capital Formation" (i.e. capital investment).

Deflators

The deflator is a composite of four equally weights parts, covering:

- maintenance and repair of machinery and equipment, including cars and other manufacturing machinery – reflecting activities to make environmental amendments to existing assets, such as the fitting of filters

- waste treatment and management – reflecting activities to reduce the environmental damage of waste from production activities, through recycling, material reclaim and other waste management techniques
- architectural and engineering services – reflecting activities to design and plan more environmentally-friendly buildings, infrastructure and urban areas, including for cleaner sources of transport
- consultancy and other professional services – reflecting activities to monitor, review and change business practices, supply chains and strategies to be more environmentally-friendly

The deflators and weights underlying each of these aggregate price indices are shown in Table E3.

Table E3 – Details of deflators used for environmental protection output

Deflator description	Source	Weight	Years covered
Maintenance and repair of machinery and equipment			
Maintenance and Repair Services of Motor Vehicles (SPPI 45.2)	HPTH	0.2	1997-2019
Repair services of machinery for domestic market (PPI 33.12)	EWMK	0.3	1997-2019
Repair & maintenance services of other transport equipment (principally trains) (PPI 33.17)	EWMP	0.05	1997-2019
Industry 33.15 (ships) output deflator	Ind defl	0.05	1997-2019
Industry 33.16 (aircraft) output deflator	Ind defl	0.05	1997-2019
Industry 33OTHER output deflator	Ind defl	0.35	1997-2019
Waste treatment and management			
Waste Collection, Treatment and Disposal Services; Materials Recovery Services (SPPI 38)	HOZL	0.5	1997-2019
Hazardous Waste; Collection Services of Hazardous Waste (SPPI 38.12)	HP9B	0.05	1997-2019
Non-Hazardous Waste; Collection Services of Non-Hazardous Waste (SPPI 38.11)	HOZN	0.05	1997-2019
Treatment and Disposal Services of Hazardous Waste (SPPI 38.22)	HPGJ	0.05	1997-2019
Treatment and Disposal Services of Non-Hazardous Waste (SPPI 38.11)	HOZL	0.05	1997-2019
Sorted Materials Recovery Services; Secondary Raw Materials (SPPI 38.32)	HPNN	0.1	2003-2019
Division 38 output deflator	Ind defl	0.1	1997-2019
Division 39 output deflator	Ind defl	0.1	1997-2019
Architectural and engineering services			
Professional, Scientific and Technical Services (SPPI M)	HSGG	0.2	2009-2019
Technical Testing and Analysis Services (SPPI 71.2)	HTCW	0.1	1997-2019
Architectural and Engineering Services; Technical Testing and Analysis Services (SPPI 71)	HSIH	0.2	2009-2019
Engineering Services and Related Technical Consulting Services (SPPI 71.12)	HT3T	0.1	2010-2019
Other Professional, Scientific and Technical Services (SPPI 74)	HUFZ	0.1	2009-2019

Division 71 output deflator	Ind defl	0.2	1997-2019
Division 74 output deflator	Ind defl	0.1	1997-2019
Consultancy and other professional services			
Professional, Scientific and Technical Services (SPPI M)	SPPIs	0.2	2009-2019
Business and Other Management Consulting Services (SPPI 70.22)	SPPIs	0.5	2011-2019
Division 70 output deflator	Ind defl	0.3	1997-2019

Notes: In Source column, four-digit codes are CDIDs (four-digit identifiers on ONS website; "Ind defl" means they are industry output deflators, sourced from here; SPPIs mean they are services producer price indices, sourced from here. The weights sum to one when all deflators are present in a given year; they are rescaled for years where not all deflators are available.

Environmental Protection Expenditure survey

Estimates of the expenditure by businesses on environmental protection are collected in the ONS' Environmental protection expenditure (EPE) survey. This samples approximately 3,000 businesses annually from industries thought to conduct the most such expenditure – namely mining and quarrying (section B), manufacturing (section C), energy (section D), and water supply (division 36).

The survey was run by Defra between 1999 and 2013, and then taken over by ONS after a one-year hiatus. There have been a number of changes to survey and sampling over time, which make the data have a number of breaks and inconsistencies. Since 2016 the survey has asked for 'internal' and 'external' current expenditure and 'integral' and 'end of pipe' capital expenditure separately. Before this, capital expenditure was included but not separately identified.

The survey data cannot be used for our work for a number of reasons. First, the industry coverage is limited to the aforementioned industries, which represent a minority of the economy. While these might be the industries most likely to produce environmental protection output, other industries clearly also have some relevant output which the survey is silent on. To ensure a consistent approach across the whole economy, we need a different approach. Second, breaks in the survey over time make use of the data difficult over a long time period. For instance, capital expenditure was included but not separately identified from 1999 to 2013 when the survey was run by Defra. Since capital expenditure will already be in GDP, we would not want to include this to avoid double counting. Not having it separately identified makes this difficult. Finally, the time series is too short and has gaps – starting in 1999 and with data in 2014 missing. While these could be estimated, it would make the estimates in these years particularly uncertain.
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