Discussion paper

Index Decomposition Analyses on changes in CO_2 emissions

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1. Introduction

In order to tackle climate change several policy targets are set to reduce greenhouse gas emissions. In order to achieve these targets several measures are being put in place.

One major policy measure relates to the energy transition. The aim is to substitute all fossil based energy carriers by renewable energy sources. In Europe, the Green Deal[1] focusses on decarbonizing the EU's energy system. For the Netherlands, RvO (The Netherlands Enterprise Agency, affiliated to the Ministry of Economic Affairs and Climate) is developing plans for an energy system in which no GHG emissions occur[2].

Other policy measures focus on circular economy and a materials transition. The relation between climate change and circular economy is more complex than that between climate and energy. However, it has been shown that climate change and material use are strongly linked with each other. Examples are the scientific studies of international renowned institutes like the International Resource Panel[3] and the Ellen McArthur Foundation[4], which are adopted by various government assessment agencies[5][6]. From primary resource extraction to production to the disposal of end-of-life products, greenhouse gas emission occur. Therefore, using less resources or extending the lifespan of materials can reduce GHG emissions. A circular economy attributes to more efficient resource use by a whole packages of strategies like e.g. recycling, re-use and re-design. Besides, the sustainable use of renewable resources instead of fossil based materials is an important feature of a circular economy. In the Dutch NPCE (National Program Circular economy[7]) it is assumed that circular measures contribute significantly to the achievement of the government target to realize an greenhouse gas emission reduction. The European Commission adopted the circular economy action plan (CEAP[8]) in 2020. The CEAP is one of the main building blocks of the European Green Deal, Europe's plan to reach climate neutrality by 2050.

The contribution of policy measures on energy and materials to the reduction of climate change is paramount in order to achieve EU's climate targets. At the same time, economic growth is considered something to strive for. Therefore we investigate factors related to material use, economic growth and the energy transition underlying changes over time in CO_2 emissions. In a preliminary investigation, we use an Index Decomposition Analysis (IDA). The IDA decomposes the change in CO_2 emissions into the changes of the various presumed driving factors.

For our IDA we apply time series that go back to 1970. Structural changes are more likely to appear in a long time perspective, as only then these changes are not masked by incidental occurrences like changes in weather conditions or economic crises. A long time analysis will therefore provide more insight for policymakers and researchers into the past, and thereby potential future structural changes that can contribute to a transition towards a more circular economy.

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[1] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en

[2] https://www.rvo.nl/onderwerpen/energiesysteem

[3] https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change

[4] https://ellenmacarthurfoundation.org/completing-the-picture

[5] https://www.pbl.nl/publicaties/hoe-kan-circulaire-economiebeleid-bijdragen-aan-de-klimaatdoelstelling

[6] https://www.eea.europa.eu/publications/improving-the-climate-impact-of

[7] https://www.rijksoverheid.nl/documenten/beleidsnotas/2023/02/03/nationaal-programma-circulaire-economie-2023-2030

[8] https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

The research under consideration is still preliminary. We would like to thank colleagues and researchers at Statistics Netherlands, Eurostat, and PBL Netherlands Environmental Assessment Agency for their valuable reflections on our research, though this investigation remains our full responsibility. We would also like to invite other researchers, policy makers and other interested readers for further discussion on the results, and underlying methodology and data.

2. IDA methodology

How do economic activity, energy consumption and material use correlate with changes in CO_2 emissions, and to what extent? We would like to quantify the relationships between these variables. In this preliminary investigation we apply the technique of index decomposition analysis (IDA). An IDA decomposes the variable under consideration (here: emissions) into a number of so called 'drivers' or factors.

In an IDA you apply a multiplicative equation for a variable Y with n factors $X(i)$:

$$Y = X(1) \cdot X(2) \cdot \ldots \cdot X(n).$$

This is converted into an additive equation for the change in Y decomposed into the contributions of changes in factors $X(i)$:

$$\Delta Y = \Delta X(1) + \Delta X(2) + \ldots + \Delta X(n),$$

Here, ΔY represents the change in emissions.

In our search for a sensible and neat decomposition of the change in emissions, we applied a preliminary IDA model from Eurostat (2022). With data for EU countries, Eurostat (2022) estimated the contributions of various factors $X(i)$ to emissions in the EU. We implemented this IDA with data for the Netherlands as part of a Eurostat grant (Delahaye *et al.*, 2022). In 2023 we further adjusted and expanded our work on the Eurostat (2022) model with alternative factors and measurements. These developments are the basis of the results presented in the current paper. We also investigated the robustness of the resulting contributions of factors to changes in CO_2 emissions. In the next sections, we present our main result. Annex A briefly describes various robustness investigations and some alternative results.[9]

The Eurostat method states that the contribution of a factor $X(i)$ to the change in Y (here: emissions) in period $[t-1, t]$ (here: two consecutive years) is calculated as the ratio between the growth rates of $X(i)$ and Y, multiplied by the change in Y: [10]

$$\Delta X(i)_t = \frac{\ln(X(i)_t) - \ln(X(i)_{t-1})}{\ln(Y_t) - \ln(Y_{t-1})} \cdot \Delta Y_t$$

We emphasize that an IDA is no causal model, but quantifies presumed interactions. Usually an IDA includes factors that are supposed to influence the dependent variable. Some factors have a clear relationship with CO_2 emissions, such as energy consumption. The impact of materials use on emissions is more complex. Our aim is to look into correlations between the change in emissions and the change of the various factors. We do not state that these factors 'cause' or 'drive' those emissions exactly with their quantified contributions.

[9] Results are available upon request.

[10] Annex A also discusses an alternative method that is technically somewhat neater, based on Dietzenbacher and Los (1998).

Further, there may be hidden and mutual relationships between the factors themselves. The causality from materials use to CO_2 emissions is not clear beforehand. A part of the impact of material use may go via use of fossil energy carriers (energetic and non-energetic). This is an indirect effect. The mentioned causality loop can artificially magnify the effect of materials use in the decomposition. There are more mutual causalities, such as that between economic factors and energy variables.

Instead, we present the decomposition as an integrated macro-economic framework in which various factors play interacting roles in the change in emissions. It is not possible to trace back parts of changes in the emissions to exactly that one factor. We pose that the IDA shows whether there are correlations, and that the quantified contributions cautiously indicate the extent of impact of the various factors. Our first aim is to show the relative contribution of factors in the three main policy themes (economy, energy and materials) within one analysis of climate change (proxied by changes in CO_2 emissions). A second main contribution of our IDA is the long time perspective, providing insight in structural changes over time. The results give an impression of developments in the past on economic growth, energy use, materials use, recycling and substitution.

3. Factors behind changes of emissions

Which relevant factors contribute to changes in emissions, and what are their relative roles? We highlight factors in three areas: economic activity, materials use and energy consumption. We take into account factors that indicate the *level of activity*, such as economic growth, primary material use and fossil fuel consumption. Besides, we apply factors indicating *shifts*, such as the shift from the goods sector to the services sector, from primary to secondary materials, and from fossil fuels to renewable energy sources. With long time series data, we may observe structural changes due to technological change and innovation, and fundamental changes in consumption behaviour.

Below we present our main model, where the CO_2 emissions in the Netherlands are decomposed into the contribution by seven relevant factors:

$$CO_2 = Prod \times \frac{Prod_G}{Prod} \times \frac{(DMIexFossil + U)}{Prod_G} \times \frac{DMIexFossil}{(DMIexFossil + U)} \times \frac{Pop}{DMIexFossil} \times \frac{E}{Pop} \times \frac{CO_2}{E}$$

We chose to measure the dependent variable with CO_2 emissions instead of total GHG emissions. CO_2 is the main greenhouse gas emerging from materials and energy consumption. Methane gas (another important greenhouse gas), for example, is mainly sourced in livestock farming.

The seven factors on the right hand side of the equation are in the three mentioned areas economy, materials and energy. Note again that there are mutual and hidden effects between the factors. Economic growth, consumption of energy and materials use are mutually correlated. However, as we noted earlier, insight in dependencies and relative contributions benefit from analysis within one model.

3.1 Economic factors

$Prod$ = gross output
Production. It is generally expected that growth of gross output or economic growth leads to an upward pressure on CO_2 emissions. Climate and circular economy policy should aim for decoupling between emissions and economic activity.

$Prod_G/Prod$ = share of the goods sector in total gross output
We define the goods sector ($Prod_G$) as comprising industries that produce, extract or use raw materials in production. These activities are generally energy intensive and produce more CO_2 emissions than the services sector. Here we measure the goods sector as the sum of output of the agriculture, mining and manufacturing (NACE A, B and C).

Due relative strict environmental regulations in Europe and the Netherlands, and the associated cost to comply with them, some companies will relocate their plants to countries with lower environmental standards. This is the so called “pollution haven hypothesis”. Over a longer run, a shift from goods sectors to a services economy leads to less direct emissions in a country, because the production structure of the total economy changes towards less material and energy intensive production. On the other hand, such a shift can lead to more import of energy intensive products and more emissions abroad (see also the Box on footprints).

Emissions in the Netherlands and the footprint

A consequence of a shift from emission intensive goods sectors to other sectors such as services in the Netherlands may be that direct emissions associated with the goods sector occur across the border, in foreign countries that will now produce these goods. Dutch producers and consumers might import these goods. This can lead to a situation of a decline in direct emissions in the Netherlands, but an increase elsewhere. It is self-evident that a local reduction in GHG emissions but, at the same time, an increase in emissions in the total production chain will not attribute to tackle climate change.

Only footprint analysis that considers emissions throughout the whole international production chain can account for the 'disappeared' emissions. Therefore footprint indicators have become common in national and international reporting on sustainability. They are, for example, part of the Dutch Monitor of Well-being and the Sustainable Development Goals 2023. (CBS, 2023) and published by Eurostat[11]. Not only GHG emission footprints but also other footprints like material use footprints are commonly being compiled.

Footprints are beyond the scope of the current paper. The main reason is that data of other countries on the drivers behind CO_2 emissions can not be obtained. Therefore, we only consider emissions directly related to Dutch economic activities.

3.2 Materials factors

$(\boldsymbol{DMIexFossil} + \boldsymbol{U})/\boldsymbol{Prod_G}$ **= material intensity**

A proxy for material efficiency. Note that the denominator $Prod_G$ refers to the gross output of the goods sector, that produces and uses most of the primary raw materials.

DMI (Domestic Material Input) is a standard measure for material use, calculated as the sum of domestic extraction of materials plus import. Another measure is DMC (Domestic Material Consumption), that also accounts for export. We apply DMI as this is more closely related to the production processes in the Netherlands.[12] Here, $DMIexFossil$ comprises primary material flows of biomass, metals and non-metal minerals. Energy is measured as a separate factor (see below).[13] The circular economy is aimed at, among other things, reduction of the use of these primary materials (see the Box on CE strategies).

The term U denotes secondary material flows of recycling from waste. The material intensity will decrease if less materials can be used for the same output. Reducing the use of materials should contribute to reduction of carbon dioxide emissions.

$\boldsymbol{DMIexFossil}/(\boldsymbol{DMIexFossil} + \boldsymbol{U})$ **= material flow linearity**

This indicator is the share of primary material flows in total material flows (excluding fossil fuels). It is the counterpart of $U/(DMIexFossil + U)$, the Circular Material Use Rate Indicator.

[11] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_carbon_footprints

[12] See also Annex A.

[13] Here, we ignore the potential overlap between energy and the other materials. At the macro-level, incineration is only a small source of carbon dioxide emissions.

The linearity ratio decreases if there is more recycling, replacing primary materials. In general recycling materials causes less emissions than production from primary materials.

$Pop/DMIexFossil$ **= population – material input ratio**

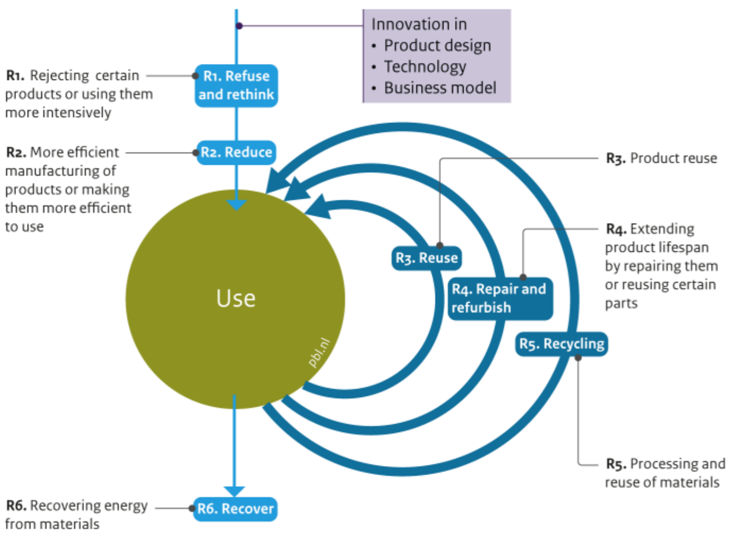
This is the inverse of DMI (excluding fossil fuels) per capita, a standard measure of the level of material input. The higher the level of $Pop/DMIexFossil$, the lower the primary resource use per capita. Over the longer run, this may indicate a transition towards less and longer use of materials, and thereby should contribute to a reduction of carbon dioxide emissions.

Circular economy strategies: the R-ladder

In our IDA, we measure the change in primary and secondary materials use. The IDA does not reveal which part of the emissions are linked to which part of material use. However, a circular economy attributes to more efficient and clean resource use by a whole packages of strategies like e.g. recycling, re-use and re-design, the so-called R-ladder (Hanemaaijer et al., 2023) The shift towards strategies higher (one being the highest) up the R-ladder are presumed to lead to lower primary materials use, and as a result less environmental impacts.

Reduction of primary materials use can most easily be related to the highest levels of the R-ladder (R1 and R2). Secondary materials use is part of R5, recycling. Here, the link with emissions is more complicated. If we recycle materials in the Netherlands this leads to additional emissions. Instead if we do not recycle but import the same (but new) material, this does not lead to emissions in the Netherlands but only to emissions abroad. Repair and re-use (R3 and R4) may lead to some additional energy use and thereby emissions. On the other hand, the fact that there are no new goods produced due to repair and re-use leads to less emissions in the country in which the production takes place. Further, our IDA is not able to explicitly specify the effects of high-quality R-strategies. This means that these effects emerge in one of the other factors in our IDA. Future development of our IDA might bring a solution to this measurement problem.

R ladder with circularity strategies



Source: PBL

3.3 Energy factors

E/Pop **= energy use per capita**
We measure energy separately in order to highlight the role of the energy transition in CO_2 emission reduction. A higher level of fossil energy consumption leads directly to higher emissions. In fact, fossil energy combustion is responsible for the largest part (around 90 percent) of carbon dioxide emissions. A part of the energy use is linked to production processes with materials use, other parts are linked to, for instance, heating or electricity, and to transport. Energy saving and a shift to renewable energy sources may prevent further emissions or even reduce them.

Here we chose to measure it as total final energy consumption (in TeraJoule), including energy from both fossil resources and renewables. We briefly discuss why we measure E in this way in Annex A.

CO_2/E **= carbon intensity of the energy mix**
With E measured as above.[14] The ratio decreases if the energy mix becomes 'cleaner' because of shifts from fossil fuel combustion to consumption from renewable energy sources.

[14] If E is measured alternatively (see Box 1 on measuring the energy indicator), the driver CO_2/E will have to be renamed. E.g. with E measured by only fossil fuels, it is not about the energy mix any more.

4. Data and measurement

The factors in the IDA are ratios of variables (except the factor $Prod$ which is no ratio). The table below describes all variables, their measurement and data sources.

The data from the Material flow accounts (MFA) and waste accounts are from a recent Eurostat research grant on long time series for MFA in the Netherlands (Delahaye et al., 2022). Additional data are from the National Accounts, Emission Accounts, and the Energy balance sheet of Statistics Netherlands[15].

Variables for the IDA

Variables	Measurement	Data source
CO_2	Emissions to air by the Dutch economy (mln kg)	Emission accounts
$Prod$	Gross output at basic prices, all economic activities A-U (mln euro, prices 2015)	National accounts
$Prod_G$	Gross output basic prices, sectors A agriculture, B mining and C manufacture (mln euro, prices 2015)	National accounts
$DMIexFossil$	Primary material flows of biomass, metals and non-metallic minerals, but excluding fossil energy carriers (mln kg). Calculated as extraction + import.	Material flow accounts
U	Secondary material flows mainly via recycling (mln kg). Recycling of materials is one of the processing methods of waste.	Waste accounts
E	Total final energy consumption, the amount of energy used by companies, households and transport in the Netherlands.	Energy balance sheet

A complete time series with consecutive annual data is available for 1995 to 2020. For the period before 1995, there are only five-year data points for some of our variables. We filled data gaps in the period 1970-1995, by linearly interpolating the data points. We do not officially publish these interpolated data, but apply these data for the benefit of the IDA on the period 1970-1995. In the Table below we show which time series had five year intervals and therefore are interpolated for our IDA. Time series for all other variables are complete from 1970 onwards. In this way, we could apply IDA on a long time period of 50 years.

[15] Note that in the meantime the IDA is published some of the CBS source data is revised and, therefore has changed. However, we are confident that these changes do not affect the overall outcome of the IDA.

Interpolation of data

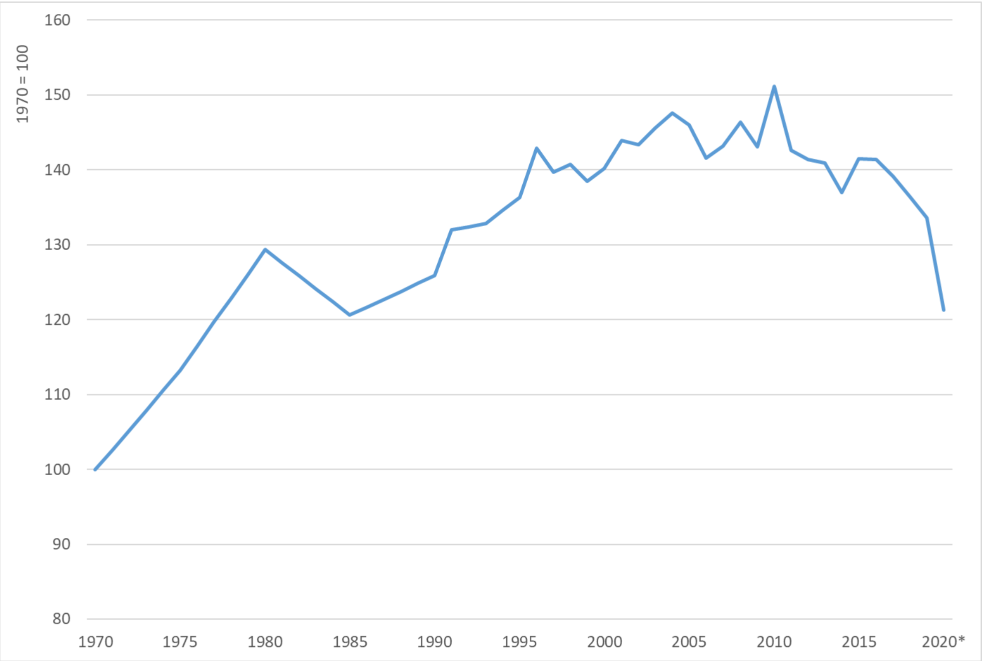
Variables	5 year data points	Annually from	Method to fill data gaps
CO_2 emissions	1970, 1975, 1980, 1985	1990	Interpolation between 5-year data points
Imports (and exports) of metals, 'other products' and waste residues	1970, 1975, 1980, 1985, 1990	1995	Interpolation between 5-year data points
Recycling from waste (U)	1970, 1975, 1980	1985	Interpolation between 5-year data points
Final energy consumption (E)	1970-1974 missing	1975	The 1970-1975 development in total energy consumption is applied for backward extrapolation

5. Results

5.1 Changes in emissions

The period 1970-2020 can be divided into a number of subperiods of 10 or 15 years: 1970-1980, 1981-1995, 1996-2010 and 2011-2020. This division is based on main changes in direct carbon dioxide emissions in the Netherlands, see Figure below. The 1970s were a decennium of strong growth in economy and population, and accompanied by strong increasing emissions. In the early 1980s, emissions were decreasing, only to increase again up to the mid-1990s. The period 1980-1995 was a period of deindustrialisation, restructuring of agriculture and industry, and lower economic growth. Thereafter, in the period 1996-2010, the service economy experienced high economic growth due to the input of ICT and higher female labour participation. This period shows a relatively slow increase in emissions. After 2010, emissions were decreasing partly due to the start of a transition towards climate friendly energy provision.

Development in CO_2 emissions in the Netherlands, 1970-2020 (index 1970= 100)



Note: Interpolations between 5-year data points in the period 1970-1990.

5.2 Changes in factors

The Table below presents the values of all seven factors for each time intervals we conducted a decomposition analyses in the period 1970-2020.[16] This shows some of the dynamics in the data. We see, for instance, a decreasing share of the goods sector over time in total gross output. Also the share of primary materials in the total of materials decreased slightly. The material intensity of production and the inverse of the material input per capita have been reduced significantly. Energy consumption per capita increased in first instance, but decreased in later periods. The carbon intensity of the energy mix seems to peak around 2010.

[16] Note that these data show the levels of the drivers, not their (annual) change.

Values of the seven factors at main time points, 1970-2020

Factors		unit	1971	1981	1996	2011	2020
$Prod$	gross output	bln euro	474,5	599,4	885,9	1273,6	1426,1
$\frac{Prod_G}{Prod}$	share of goods sector	share	0,30	0,30	0,29	0,26	0,25
$\frac{(DMIexFossil + U)}{Prod_G}$	material intensity	kg/eur	1,13	1,10	0,99	0,93	0,89
$\frac{DMIexFossil}{(DMIexFossil + U)}$	material flow linearity	share	0,93	0,90	0,84	0,84	0,84
$\frac{Pop}{DMIexFossil}$	population – material input ratio	capita/ kg	87,1	79,3	71,8	63,5	66,2
$\frac{E}{Pop}$	energy cons. per capita	GJ/ capita	116,7	129,9	136,6	116,6	100,5
$\frac{CO_2}{E}$	carbon intensity of energy mix	kg/MJ	0,095	0,098	0,096	0,104	0,098

5.3 Contribution of factors 1970-2020

In the Figure below we show the IDA result for the total period 1971-2020. Note that one should read the years as the change between the year t-1 and the current year t. E.g. 1971 represents the change between 1970 and 1971, and so forth.

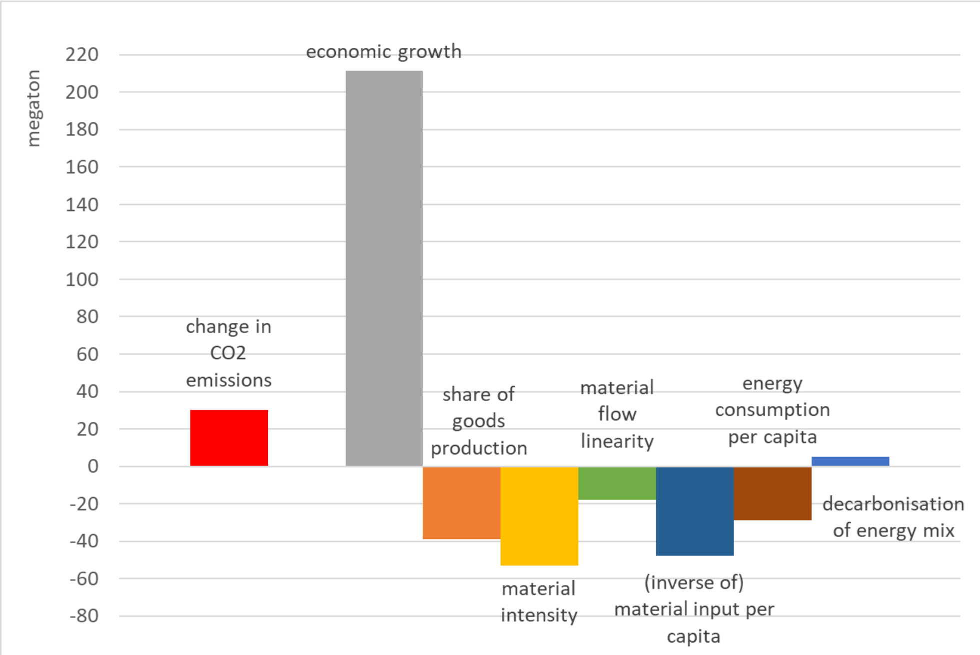
The red bar on the left in the Figure shows the total change in direct CO_2 emissions in the Netherlands in the period under consideration. When adding up all yearly changes in emissions over the whole period, we see that emissions increased on balance.

To the right of the red bar in the Figure, we see the contributions of the seven factors to the changes in emissions. This should be read as follows. For instance, the grey bar shows the volume of emissions which would have been taken place if only economic growth determined emissions and other factors did not have had a dampening effect. If one adds up all seven contributions, the result is the size of the change in emissions in the red bar.

In this long period of 50 years, economic growth has had the largest impact on CO_2 emissions. But the growth of the services sector relative to agriculture and manufacturing had a moderating impact on the volume of CO_2 emitted in the Netherlands.

The volume of used materials, and whether these were secondary or new materials, affected CO_2 emissions in a downward way. Finally the amount of energy used and the more frequent use of renewable instead of fossil energy also had an influence on emissions, though in opposite ways.

Decomposition of change in CO2 emissions in the Netherlands, 1971-2020



5.4 Contribution of factors by subperiod

We decomposed the change in emissions by subperiod, in order to reveal structural changes in the contribution of the factors over time. The Figure below summarizes the developments in the four subperiods. In this Figure we added up the contribution of the factors by theme (economy, materials and energy). E.g. we added up the contributions of production and the share of the goods sector to a total 'economic' factor.. Detailed Figures with the seven factors by subperiod and discussion are given at the bottom of this section.

The horizontal red bar in each of the columns in the Figure shows the total change in CO_2 emissions in the subperiod under consideration. One can see that emissions increased on balance in each subperiod up to 2010, only to decrease after 2010.

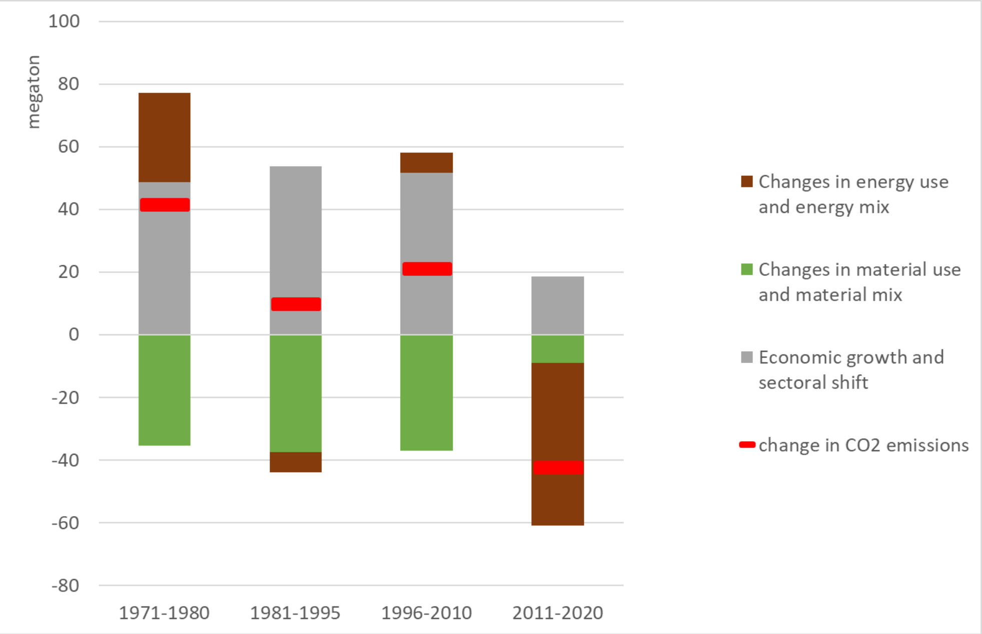
For each subperiod, the contribution by each theme (economy, materials and energy) is indicated by its own color. We can clearly see differences in these contributions over time.

Between 1970 and 2020, smarter use of materials and more recycling went hand in hand with lower CO_2 emissions. Until 2010, different use of materials helped reduce CO_2 emissions to a reasonable extent. This was mainly due to smarter use of materials and slightly less due to more recycling of materials. Since 2011, the influence of smarter use of materials seems to have become much smaller.

Yet emissions increased up to 2010, because strong economic growth. Of all factors, economic growth had the greatest influence on the increase in CO_2 emissions. This increase was partly offset by a sectoral shift in the economy. The service sector continued to expand to a larger extent as the emission intensive industry.

From 2011 to 2020, the lower consumption of fossil energy was mainly the reason for the decrease in CO2 emissions. Energy consumption per inhabitant also decreased. This is partly due to the transition to renewable energy.

Decomposition of change in CO2 emissions in the Netherlands in four subperiods, 1971-2020



5.5 Contributions of factors in detail

5.5.1 Economic factors

In the transition toward a low carbon and a circular economy, it is necessary to decouple economic activity and emissions, mainly of the goods sector. However, we observe first and foremost that economic growth is the dominant factor, with a large upward effect on CO_2 emissions. Only after 2010, its contribution decreased significantly, and at that time, emissions also decreased. The explanation is most likely in the decline in economic growth after the 2008 crisis. But it still has an upward effect after 2010.

Further, the share of the goods sector (agriculture, mining and manufacturing) in the total economy was still high in the 1970s, contributing to an increase in emissions. However, after 1980 the shift away from 'heavy' industries to services accelerated. The contribution of the NACE A, B and C sectors to the direct emissions in the Netherlands consequently declined. After 2010, the shift slowed down somewhat. As mentioned earlier, the sectoral shift may have led to a shift of emissions abroad. Our imports of energy intensive products might have increased and our footprint enlarged (CBS, 2023a).

5.5.2 Materials factors

A materials transition and transition to a circular economy are enhanced by reduction of primary material use and increase of secondary materials from recycling. In nearly all cases (materials factors and subperiods), the materials factors had a dampening impact on CO_2 emissions.

First, in all subperiods a lower material intensity (primary and secondary materials per euro production) went hand in hand with a reduction in CO_2 emissions.

This is also the case for the circular material use rate indicator, though its contribution seems to disappear altogether in later subperiods. The latter indicator states that relatively less primary materials use (and relatively more recycling) may lead to lower emissions. The contribution of this factor is lower than might be expected. However, this can be explained by the limited volume of recycling compared to the volume of primary materials. If recycling increases in the nearby future, the contribution of circularity also increases. However, in the Netherlands the recycling percentage is already relative high, around 80 percent. Therefore, other CE strategies or high grade recycling might be more viable to reduce environmental impact than trying to increase the recycling percentage.

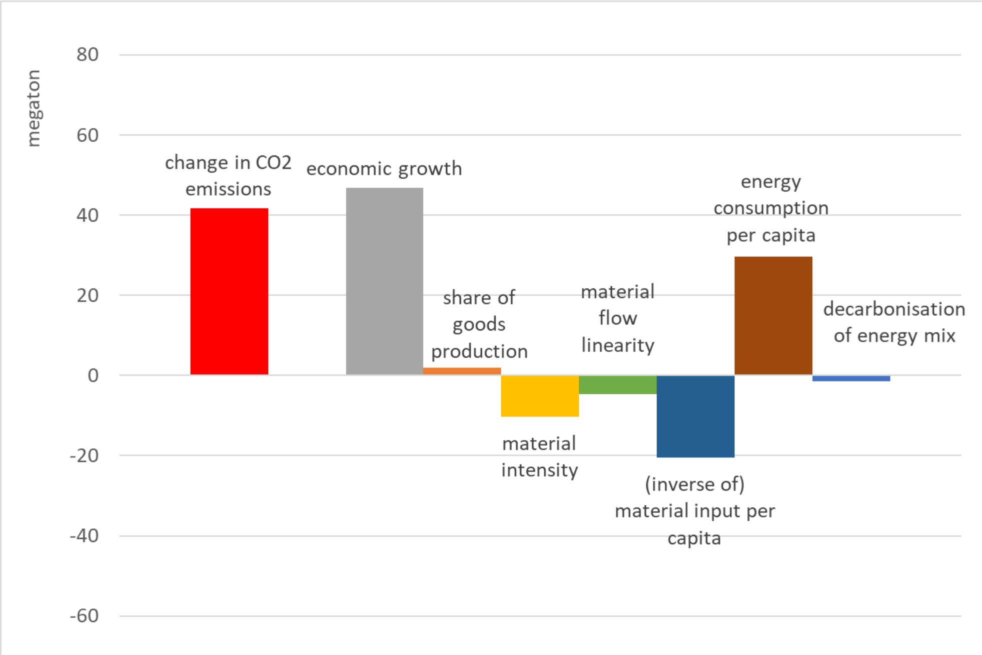
Up to 2010, the contribution of the inverse of primary materials input per capita had a dampening effect on CO_2 emissions. From 2011 onwards, the impact turned into an upward one, though very small.

5.5.3 Energy factors

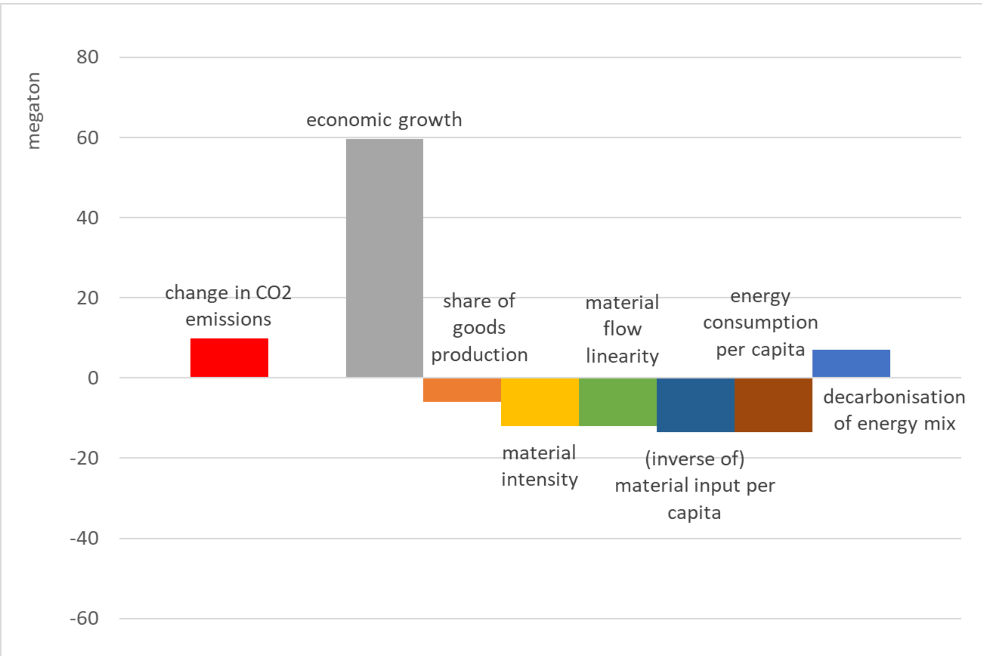
Energy saving on fossil fuels and the transition to clean and sustainable energy sources is an essential part of climate and circular economy policy. Before 1980, final energy consumption per capita had an upward effect on emissions, only to flip to a small downward impact between 1981 and 1995. The contribution of the factor was very small or nearly zero between 1996 and 2010. In the last subperiod (2011-2020), energy consumption per capita suddenly shows a large downwards effect on emissions.

The emergence of sustainable energy, cleaner technologies and energy saving measures apparently led to lower energy consumption per capita. In all subperiods, the contribution of the decarbonization of the energy mix remains relatively small. The indicator on energy comprises fossil resources and renewables. At first, the share of fossil energy consumption in the energy mix is very high, leading to more emissions before 2010. In the Netherlands, natural gas from Groningen remained an important source of energy. As a result, the Netherlands lagged behind in the shift to renewable energy sources until more recently. By now, the energy mix changes in favor of renewables.

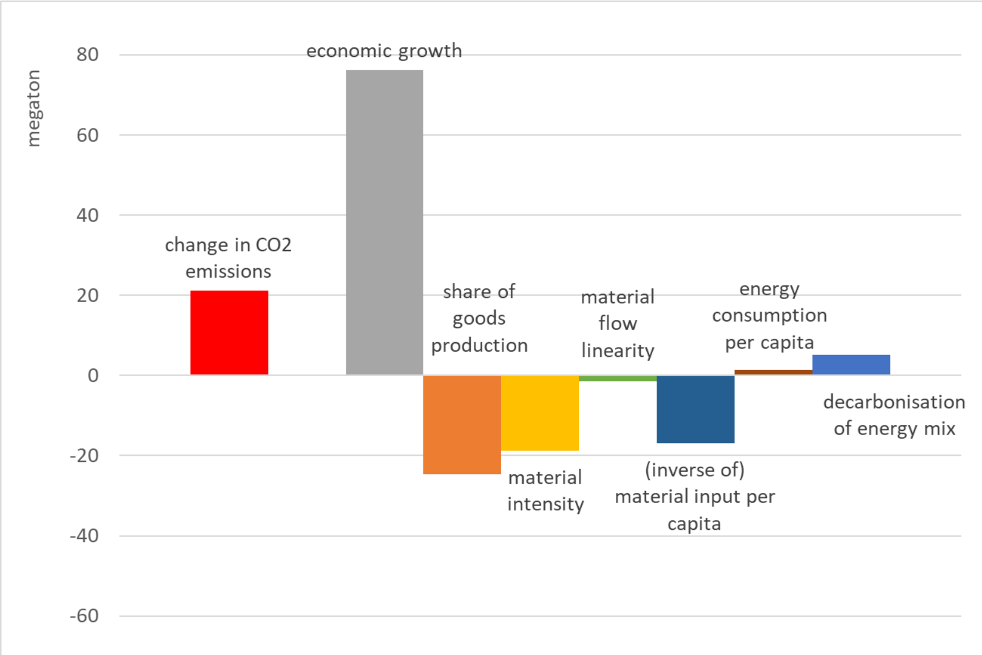
Decomposition of change in CO2 emissions in the Netherlands, 1971-1980



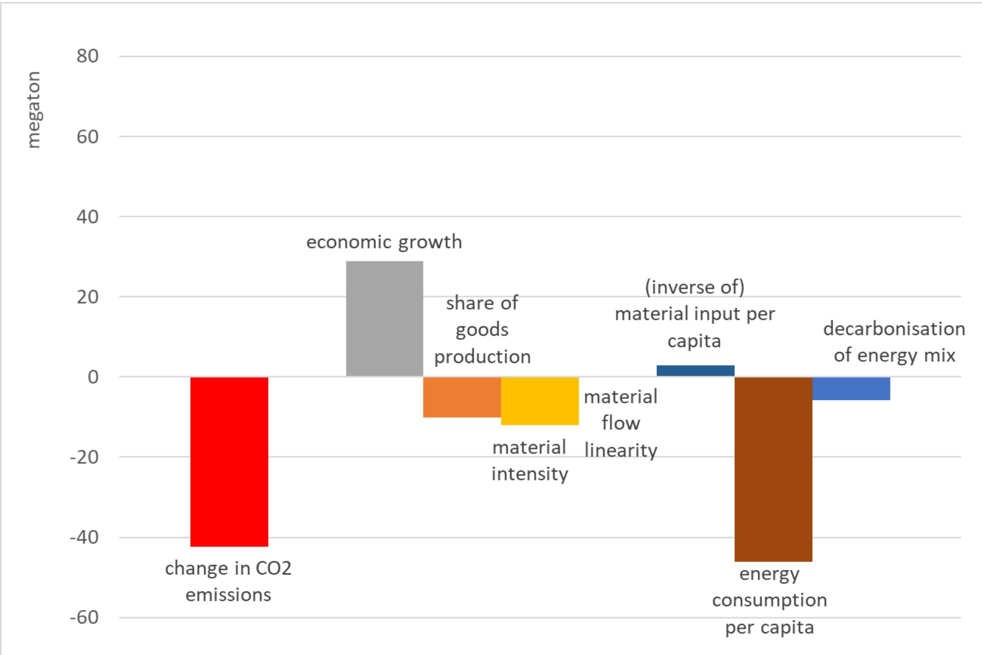
Decomposition of change in CO2 emissions in the Netherlands, 1981-1995



Decomposition of change in CO2 emissions in the Netherlands, 1996-2010



Decomposition of change in CO2 emissions in the Netherlands, 2011-2020



6. Reflections

In the current paper, we presented a preliminary investigation into an index decomposition analysis (IDA) of CO_2 emissions in the Netherlands. Our main result shows that between 1970 and 2020, smarter use of materials and resources, and more recycling, went hand in hand with lower CO_2 emissions. Yet total emissions increased because the economy grew strongly. From 2011 to 2020, less and more renewable energy use played a role in the decrease in CO_2 emissions.

We emphasize that our preliminary results have to be interpreted carefully. The relationship between dematerialization of the economy and reduction in carbon dioxide emissions is still subject of research. The decomposition analysis does not present a causal link but can uncover correlations. We would like to invite policy makers and researchers to discuss our methodology, data and results. We aimed to contribute by decomposition analysis of CO_2 emissions in two ways:

- An integrated framework of factors underlying CO2 emissions. There are factors in three policy areas: economy, energy and materials. Our aim was to look into correlations between the change in emissions and the change of the various factors. Quantified contributions cautiously indicate the extent of direct impact of the various factors.
- A long time perspective. Our IDA revealed, among other things, that the phenomena of dematerialisation and emissions apparently go hand in hand over time. The results shows the potential of long time series data for an analysis providing insight in structural changes in economy, energy and materials over time.

There are various potential alternative lines for future research. We might investigate alternatives for our IDA equation, such as changing places (within the equation) of the variables for materials and energy; or move population to the economic part, thereby linking energy directly to materials use. We already presented some exercises in the Annex, with replacing DMI by DMC, and by splitting households and economic activities (where the latter IDA comprises a factor linking energy use directly to material input). One might also discuss the definition of the ‘goods sector’ (now being NACE A to C), and extend it to relevant sectors such as construction.

Or one might rather aim to investigate decompositions on individual factors, such as a decomposition of materials or a decomposition of energy. Statistics Netherlands already did a decomposition of abiotic materials in the Netherlands (Delahaye and Couzy, 2020), which we aim to update in the near future. Further, Eurostat (2023) recently investigated decomposition analyses of energy use in various economic sectors and by households in EU countries.

Other lines of research are more related to data challenges. For instance, input-output analysis of production chains and footprints (with international linkages). Another research line is, instead of a macroeconomic analysis, the direct linking of products to their own contribution to CO_2 emissions (e.g. in the Material Flows Accounts, or the Materials Monitor). Particularly in the conversion of raw resources to materials, among other things in the basic metals industry, basic chemicals, and construction, we see that energy use and carbon dioxide emissions are related to material use, but in other sectors there is hardly no or no strong relationship.

However, such data exercises are very extensive and also bring their own data and measurement issues, whereas we currently just aimed for a first impression of potential relationships in an integral long run framework.

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Annex A. Robustness and alternatives

In the implementation of our IDA, we investigated the robustness of the resulting contributions of factors to changes in CO_2 emissions. In the article we only present our main result. This Annex briefly describes various robustness investigations and some alternative results. All results are available upon request.

A.1 Dietzenbacher-Los method

A disadvantage of the Eurostat (2022) approach (see section 2. IDA Methodology) is that it applies natural log to calculate growth rates, which gives errors or problems if numbers are negative or changes are very large.

Another IDA approach by Delahaye and Couzy (2020) is technically neater. This calculates an average of the contribution of a factor in a year from a system of equations comprising variants which resemble each other very closely. In turn, their mathematical system is based on an decomposition approach by Dietzenbacher and Los (1998). The main disadvantage is that the number of equations increases sharply with the number of factors in the IDA. We refer to Delahaye and Couzy (2020) for more detail on their method.

We applied the Dietzenbacher-Los method to our data, calculating averages but also standard deviations. We found that the results are similar to that of the Eurostat method. This gives a validation of the Eurostat approach. We chose to apply the Eurostat method in the current paper, because it is intuitive and easily explained. It can also be implemented straightforwardly in a spreadsheet (Excel) or in a programming language (R).

A.2 Data measurement

Section 4 describes the measurement of the factors for our main IDA. We discussed on how to measure the variables and which data sources are to be applied. Various possibilities came along, of which we would like to highlight two main issues: one on primary materials use and the other on energy use.

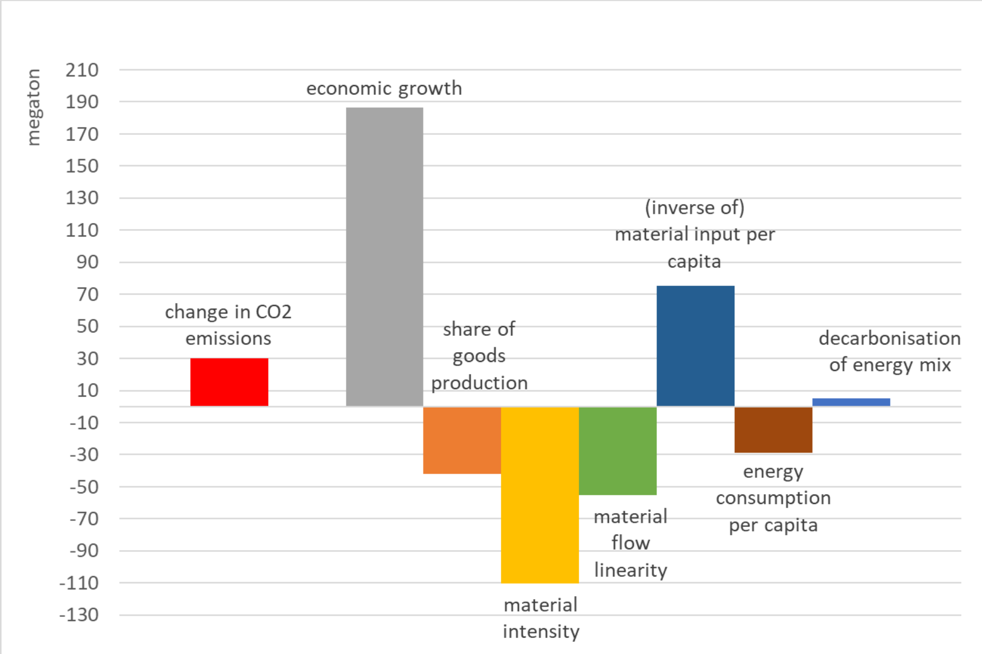
A.2.1 Measuring primary materials use: DMI or DMC

In our IDA (see section 5) we measured materials use with DMI, the sum of domestic extraction of materials plus import. We applied DMI as this is more closely related to the production processes in the Netherlands. Another standard measure is DMC, which is the sum of domestic extraction of materials plus import minus export (or DMI minus export). DMC is often the measure in comparisons between countries.

We tested whether DMC would lead to different results compared with DMI. As DMC is an consumption indicator, it should in the IDA go together with value added instead of gross output or production. So we replaced DMI and production by DMC and value added (see Figure below).

The size of the contributions of the various factors changed but their relative roles remain similar. One exception is the contribution of Pop/DMC. Where Pop/DMI has a negative sign and thereby reduces emissions, Pop/DMC has a positive sign, leading to *more* emissions. The exports of materials seem to play a role that blurs the impact of materials use in the Netherlands on Dutch emissions.

Replacing DMI and production by DMC and value added: decomposition CO2 emissions in the Netherlands, 1971-2020



A.2.2 Measuring energy E

We tested the model with a number of alternative measures for the energy indicator (E). These alternatives were applied:

- Fossil energy carriers (kg), from our database on long time series for material flow accounts (Delahaye et al., 2022). However, this does not comprise renewable energy sources that cannot be expressed in kilograms (e.g. electricity), whereas we aim to quantify structural changes in the energy mix.
- Final fossil energy consumption (TJ), excluding electricity from renewables and other non-fossil use. In this measure, renewables are also not accounted for.
- Gross inland energy consumption (TJ).[17] This measure accounts for both fossil fuels and renewable energy sources. However, as the measure is a gross quantity, it includes energy conversion as well as final consumption. This might comprise double counting in energy use leading to emissions.
- Final energy consumption (TJ), our choice for measuring energy in the IDA. Including renewable energy consumption, but avoiding the double counting problem as in the total gross energy consumption measure.

[17] Eurostat (2022) applied this measure as EU country time series were more complete than the EU data for material fossil fuel flows.

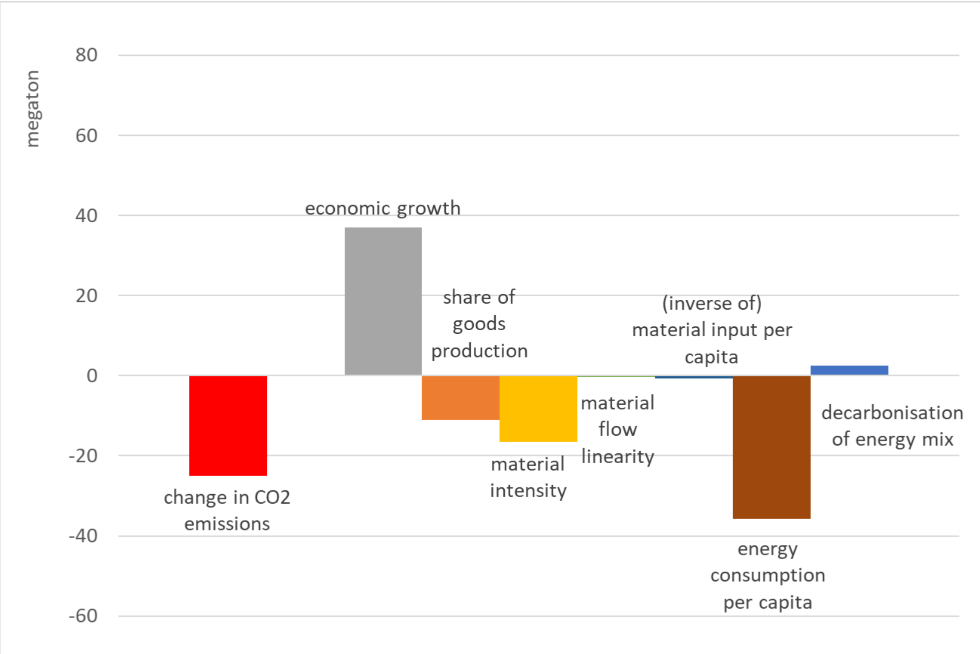
A.3 Impact of short-term changes

What impact might important incidental changes such as economic crises have on the results of our IDA? A clear example is corona in 2020. As the economy went into a lockdown, economic activity decreased for some sectors, and particularly the consumption of fossil fuels went down.

To show the difference, the Figure below excludes the year 2020 from the IDA in the last subperiod from 2011 onwards. Comparing this to the Figure including 2020 (see section 5), we observe that the decrease in energy consumption per capita in 2020 is linked to a strong decrease in the carbon dioxide emissions in that year. As the decarbonisation of the energy mix also comprises fossil fuels, we see also a, though small, difference here. Without corona, the energy mix was less decarbonized. The impact of the other factors also differs somewhat, mainly that of economic growth and material intensity.

But fundamentally our conclusions do not change by this, though important, short-term change: after 2010, reduced energy consumption lead to lower emissions.

Short-term impacts: decomposition of change in CO2 emissions in the Netherlands, 2011-2019 (without corona year 2020)



A.4 Alternative IDAs

We investigated different variants on our main IDA model in section 3. Among other things, we discussed whether the goods sector should be defined more broadly by including NACE D, E and F. In the end we decided to leave these NACE classes out because they represent service activities that in essence different from the production of goods.

Here we show the results of two variants. First, we built up the model by starting with a few factors, and extend it by adding more factors. This in order to show the robustness of the factors' contributions.

Second, we split the households from the economic activities. The role of households in energy consumption might blur or bias the results for economic activities leading to emissions. We did not decompose CO_2 emissions at lower sectoral level (e.g. NACE Letter level), as the material variables (DMI and DMC) are not conceptually sound at that level. Even splitting up between households and economic activities might be not appropriate, as households are also using materials. We assumed that all materials are used up in production processes of economic activities, and the resulting products being consumed by households.

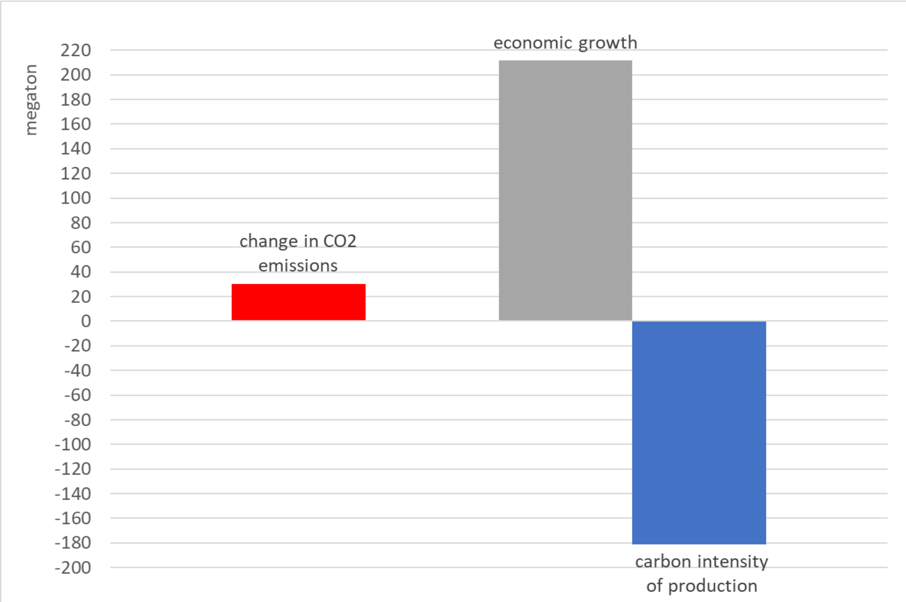
A.4.1 Variant 1: Building up the IDA

We built up our IDA in five steps, with each step we show the results. We observe that in each model, the economic factor remains dominant. However, the carbon intensity of the factors in the models under consideration hide various changes. We see in extending with relevant factors that there is more behind measured economic growth or use of primary materials. There are also the interacting factors of secundary materials use and energy use. Further we see that the signs of contributions of factors are what we expected. Increased materials efficiency, more use of secondary materials, reduced energy consumption and more use of renewables go hand in hand with a reduction of emissions.

1. Start with economic activity and emission intensity (decoupling of production and emissions)

$$CO_2 = Prod \times \frac{CO_2}{Prod}$$

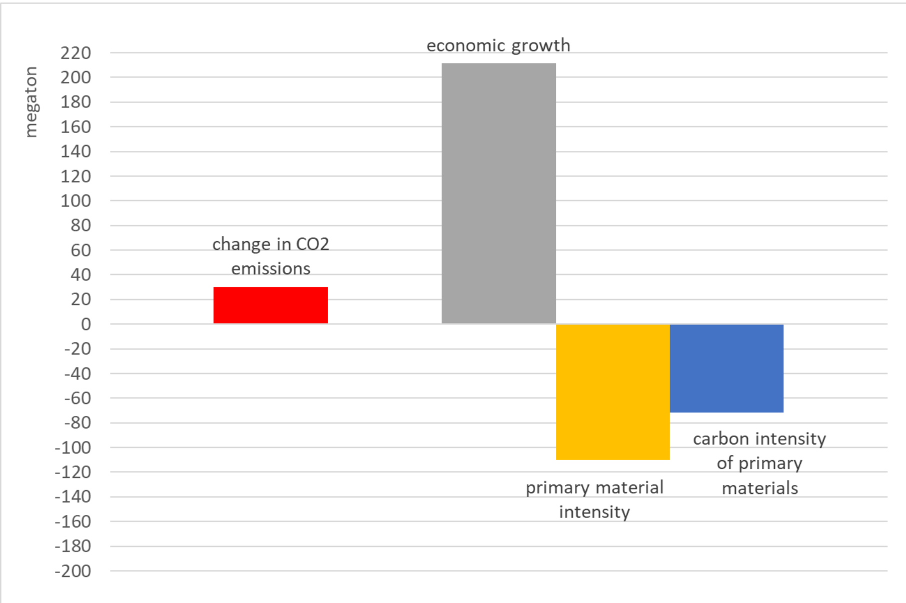
Model 1. Economic growth: decomposition of change in CO2 emissions in the Netherlands, 1971-2020



2. Extend the model with primary materials (less depletion of primary materials)

$$CO_2 = Prod \times \frac{(DMIexFossil)}{Prod} \times \frac{CO_2}{(DMIexFossil)}$$

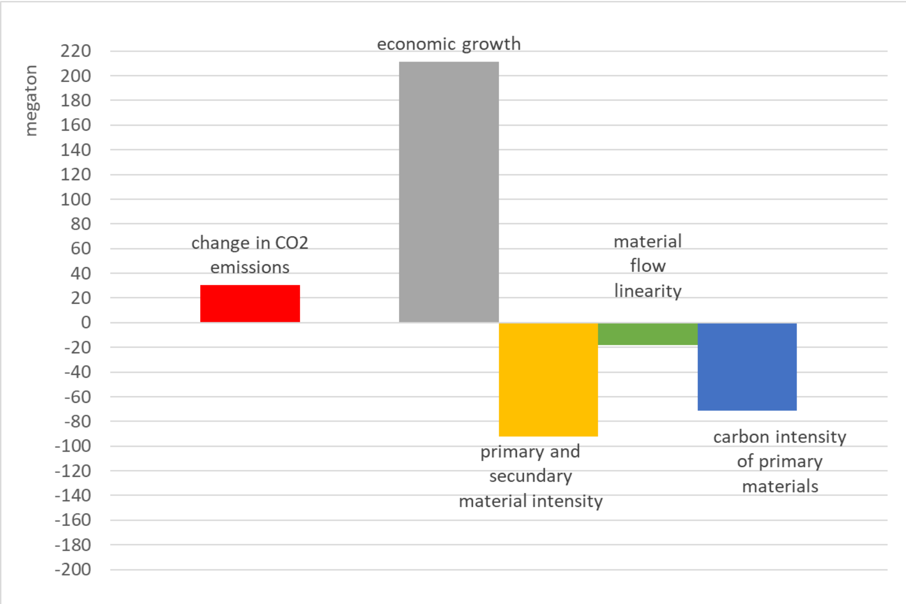
Model 2. Adding primary materials: decomposition of change in CO2 emissions in the Netherlands, 1971-2020



3. Add the recycling effect (shift in the materials mix, structural change)

$$CO_2 = Prod \times \frac{(DMIexFossil + U)}{Prod} \times \frac{DMIexFossil}{(DMIexFossil + U)} \times \frac{CO_2}{DMIexFossil}$$

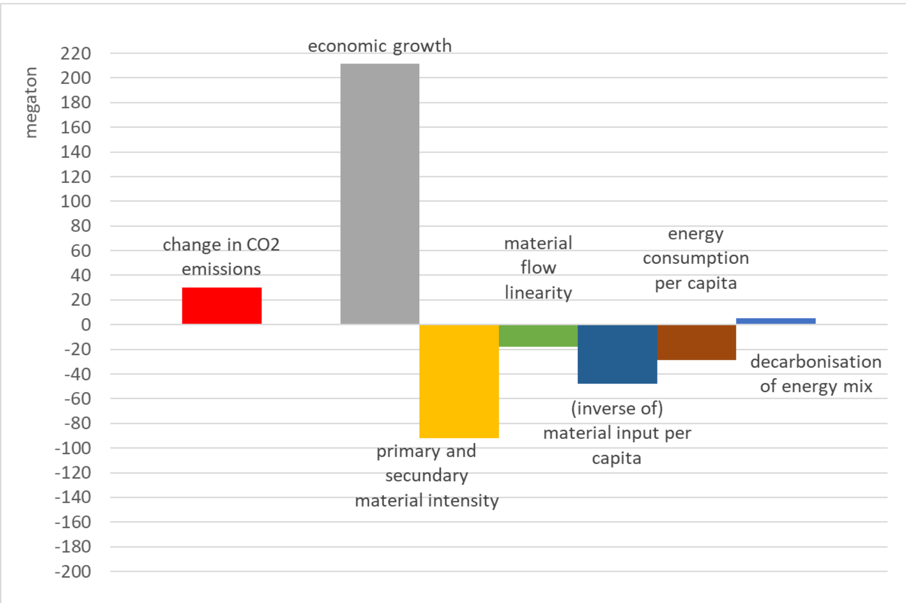
Model 3. Adding secundary materials: decomposition of change in CO2 emissions in the Netherlands, 1971-2020



4. Extend with energy use, which introduces also population (reduction of energy consumption and shift to renewables, structural change)

$$CO_2 = Prod \times \frac{(DMIexFossil + U)}{Prod} \times \frac{DMIexFossil}{(DMIexFossil + U)} \times \frac{Pop}{DMIexFossil} \times \frac{E}{Pop} \times \frac{CO_2}{E}$$

Model 4. Adding energy and population: decomposition of change in CO2 emissions in the Netherlands, 1971-2020



5. Finally add the shift to services sectors (economic structural change)
This model is the final model presented in section 5, the reader is referred to this section.

A.4.2 Variant 2: Households and economic activities

Splitting up households and economic activities (NACE A to U) implies that both have their own equation of decomposing factors behind the changes in CO_2 emissions. Households are not producing, so the decomposition equation for households does not comprise economic and materials factors. We assumed that all materials are used up in production processes of economic activities, and the resulting products being consumed by households. Only population growth, energy consumption and use of renewable energy resources are in the equation for households (h):

$$CO_{2,h} = Pop \times \frac{E_h}{Pop} \times \frac{CO_{2,h}}{E_h}$$

For total economic activities (t) without households, population growth is only an indirect factor. The growth of the economy partially captures changes in demand as a consequence of population growth. Here, we propose the following decomposition:

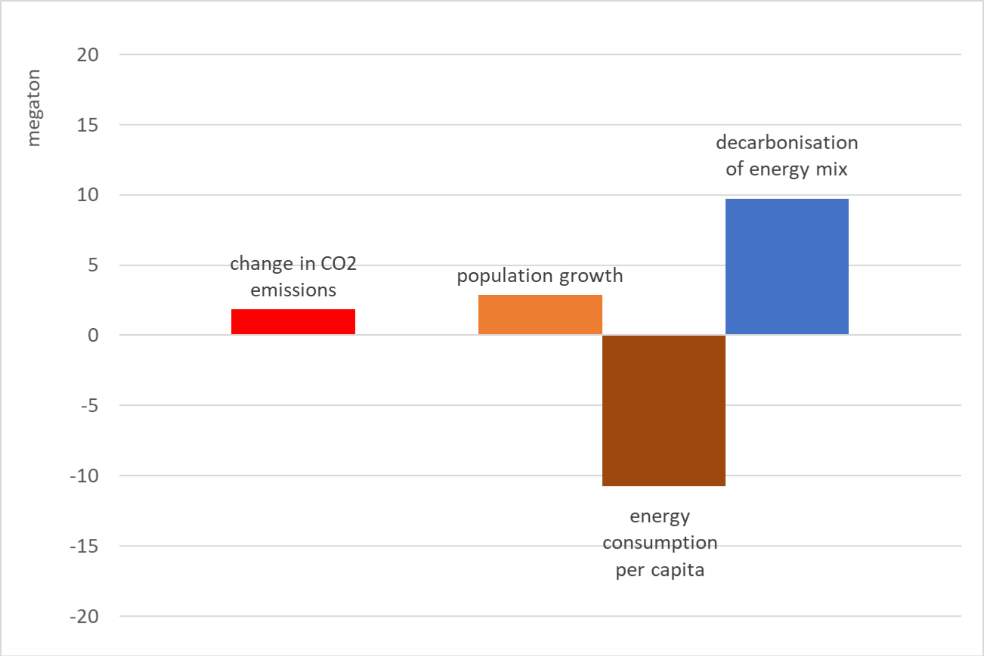
$$CO_{2,t} = Prod \times \frac{Prod_G}{Prod} \times \frac{(DMI_{123} + U)}{Prod_G} \times \frac{DMI_{123}}{(DMI_{123} + U)} \times \frac{E_t}{DMI_{123}} \times \frac{CO_{2,t}}{E_t}$$

where *E/DMI* denotes the energy efficiency of material input.

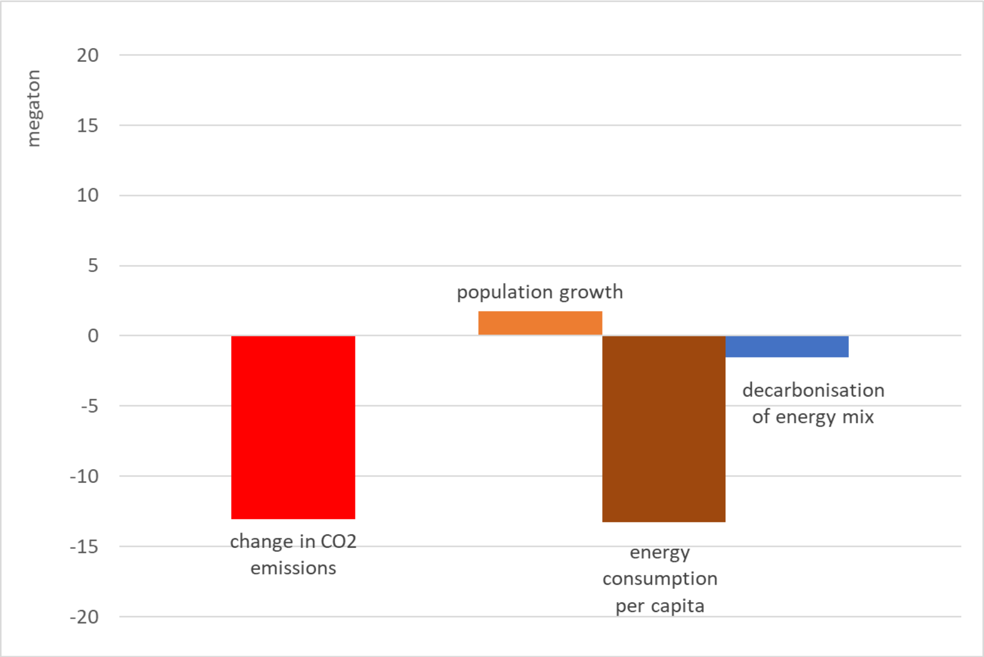
With the division between households and economic activities, there are less data available. The time series become shorter, with 25 years from 1995 to 2020. With these data we nevertheless can compare to results of the main IDA for the last two subperiods presented in section 5. Note that the Figures for the households are presented on another scale than that of economic activities (and the individual periods in section 5).

We see that energy consumption per capita already went downwards for households in the period 1996-2010. However, there was still no shift in the energy mix, the use of natural gas by households was widely spread in the Netherlands. Only by the last subperiod there seems to be a shift to cleaner energy sources such as heat from biomass power plants and solar panels. In the economy itself we see a comparable pattern as in the macro-analysis of section 5. The reduction of energy efficiency of material input has presumably a downward impact on CO_2 emissions of the economic activities, consuming less energy in production processes, particularly from 2011 onwards. A striking result is the large dampening contribution of the decarbonisation of the energy mix in the same subperiod. This shift to renewables by economic activities seems to be blurred by households' activities in the main IDA of section 5.

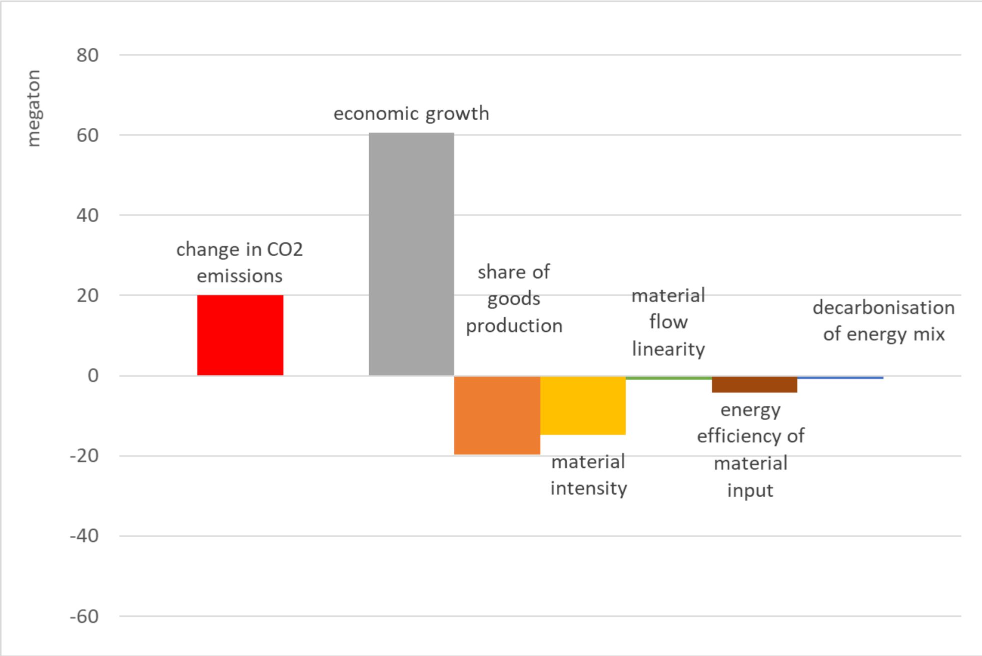
Households: decomposition of change in CO2 emissions in the Netherlands, 1996-2010



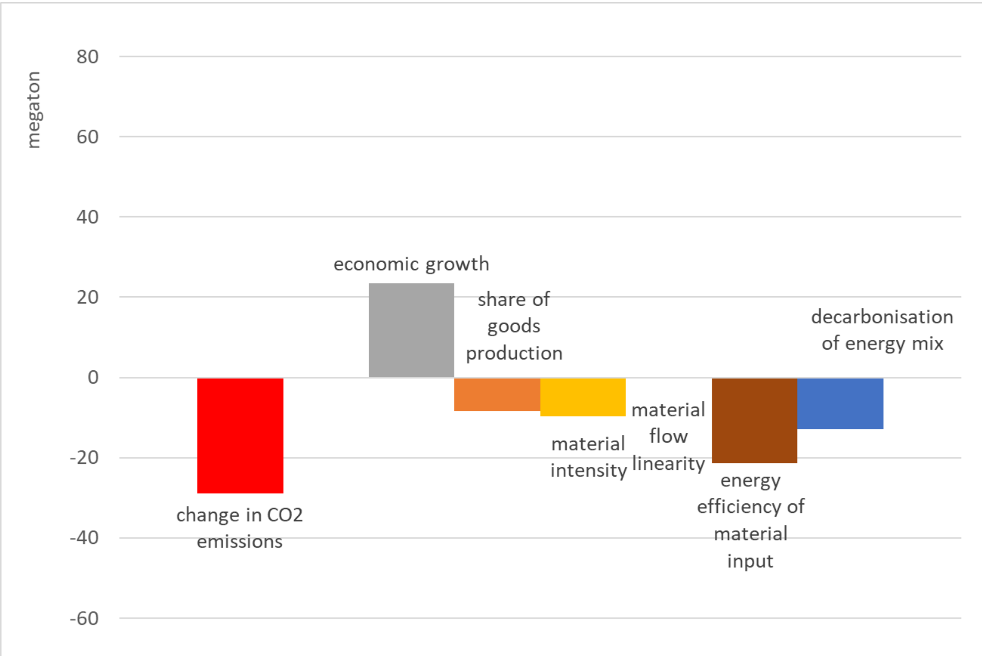
Households: decomposition of change in CO2 emissions in the Netherlands, 2011-2020



Economic activities (NACE A-U): decomposition of change in CO2 emissions in the Netherlands, 1996-2010



Economic activities (NACE A-U): decomposition of change in CO2 emissions in the Netherlands, 2011-2020



Explanation of symbols

Empty cell	Figure not applicable
.	Figure is unknown, insufficiently reliable or confidential
*	Provisional figure
**	Revised provisional figure
–	(between two numbers) inclusive
0 (0.0)	Less than half of unit concerned
2022–2023	2022 to 2023 inclusive
2022/2023	Average for 2022 up to and including 2023
2022/’23	Crop year, financial year, school year, etc., beginning in 2022 and ending in 2023
2020/’21–2022/’23	Crop year, etc., 2020/’21 to 2022/’23 inclusive

Because of rounding, some totals may not correspond to the sum of the separate cells.
Revised figures are not marked as such.

Colophon

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