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Laurence Bloch, Dominique Bureau

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CREST
Center for Research in Economics and Statistics
UMR 9194

5 Avenue Henry Le Chatelier
TSA 96642
91764 Palaiseau Cedex
FRANCE

Phone: +33 (0)1 70 26 67 00
Email: info@crest.science
https://crest.science/

Expanded National Accounts for the Environment

Laurence Bloch[1] Dominique Bureau[2]

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Abstract

We develop a framework to consistently integrate environment into the national accounts system: on the one hand, environmental assets into the asset accounts, and, on the other hand, the ecosystem services they provide, as well as the degradation or improvement of these assets linked to human activities, into the flow accounts. Based on the methodology proposed by Muller *et al.* (2011), we use the Pigouvian valuation of externalities: the cost (benefit) of the present and future damages (services) they generate. We specify the building of supply and use balances for these new services and the various adjustments to the different current and asset accounts. We derive adjusted synthetic indicators of economic activity and income, as well as saving, investment, and wealth. Generalized to take into account the rest of the world, this framework integrates cross-border pollution and global public goods such as climate.

Keywords: national accounts, environmental damages, externalities, global public goods, adjusted aggregates
JEL codes: D62, E01, H23, H40, I31, I51

[1] CREST-ENSAE affiliate. Email: laurence.bloch@ensae.fr.
[2] Corresponding member of the Economic Analysis Council, Paris. Email: dominique.bureau@sgp.fr.

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Introduction

Measuring natural capital, estimating environmental damage and their valuation have been at the heart of environmental and welfare economists' concerns for more than 50 years, as recently highlighted in the Dasgupta review (2021). With a view to broadening national accounts to assess the sustainability of our development, the report underlines that, in order for environmental issues to be properly taken into account in collective decision-making, economic success indicators need to be modified. In particular, Gross Domestic Product (GDP), which does not account for the depreciation of natural assets, encourages us to pursue unsustainable economic growth and development.

Various initiatives have already been taken in this direction, notably the World Bank and UNU-IHDP & UNEP reports on the wealth of nations (2011) and inclusive wealth (2012). At the same time, international thinking on the integration of natural heritage into national accounts and the consideration of the degradation of natural assets by economic activities is progressing rapidly, influenced in France in particular by Vanoli (1995, 2014, 2015, 2017). Thus, the SEEA 1993 (System of Environmental Economic Accounts), the first version of an integrated economic and environmental accounting system (United Nations, 1993), focuses on defining and measuring the environmental costs of economic activities. It was followed by new versions in 2003, 2012, and 2021(see United Nations (2007, 2014, 2024)).

However, in the latest 2021 version (United Nations, 2024), the chapters relating to the valuation of ecosystems in the SEEA-EA (Ecosystem Accounting) section, which, like the SNA (System of National Accounts), are based primarily on the concept of exchange value (the market price, where it exists), have not been adopted due to a lack of international consensus. As for the SNA in its latest 2025 revision (United Nations, 2025), it only includes modest changes to the accounting of natural capital. Certainly, the classification of natural assets has been expanded to include renewable energy resources (solar and wind electricity, hydroelectric assets), and the split-asset approach has been implemented for the distribution of operating income between extractors and legal owners. However, the valuation of natural assets continues to be based on the concept of exchange value. And while the depletion of natural resources is now recorded as a production cost and deducted from net domestic product (NDP), as is the consumption of fixed capital, this does not result in any change in GDP.

Of course, various national statistical institutes, notably the ONS in the United Kingdom (Heys *et al*. (2024)) and INSEE in France (Larrieu & Roux, 2024), have recently proposed expanded national accounts and new modified aggregate indicators, particularly for the measurement of saving. However, these separate country accounts do not ensure complete consistency between flows and stocks, only partially take into account the global public good dimension of air quality, and are not constructed in a perspective of aggregation at the global level. These various attempts to integrate the environment into national accounts fundamentally run up against the constraint of implementing the SNA's price and volume concepts, which are essentially based on exchange value. Their methodologies appear fragile, particularly as they ignore the non-market dimensions of natural assets and various market failures, especially the externalities associated with the services provided by natural assets.

In this context, we are developing an accounting framework to expand the national accounting system in a consistent way. This framework integrates, on the one hand, environmental assets into the wealth accounts and, on the other hand, the ecosystem services they provide, as well as the degradation or improvement of these assets linked to human and economic activities, into the flow accounts. Moreover, we strive to ensure the consistency of the full sequence of economic accounts, from the production account to the capital account, by clarifying the associated concepts of income and savings, and the appropriate aggregation of the different accounts, from the national to the global level, particularly in the case of the integration of transnational pollution or global public goods such as the climate[3].

For this purpose, we draw on the approach of Muller *et al*. (2011) which focused on taking into account the externalities linked to air pollution emissions in the production accounts of industries. Their study was undertaken during a time of controversy over the impact on US productivity of the Clean Air Act, initially adopted in 1970, then strengthened in 1977 and amended in 1990. Using the so-called Pigouvian valuation of externalities, at their social value, corresponding to the present and future costs of air pollution damages, Muller *et al*. (2011) estimated the contributions of different industries to aggregate air pollution damages. They also built adjusted production accounts for the different industries, taking into account the source of the pollution emission. Following this approach, we explore the consequences up to the capital account, linking it to the approach to sustainability and inclusive wealth developed by Arrow *et al*. (2012) and the World Bank (2011, 2021, 2024). The applicability of this approach is thus generalized to various externalities linked to economic activity and services provided by natural assets.

The production boundary for goods and services is extended to include service flows (positive or negative) directly associated with externalities linked to economic activity. It is also extended to include service flows provided by environmental assets - whether or not they give rise to a market transaction - the latter being included in the asset boundary.

We specify the construction of new supply and use balances for these new services and the various adjustments to be made to the existing ones, as well as to the production, the different income and the capital accounts, and the asset accounts. From this point, we derive adjusted synthetic indicators of economic activity and income, as well as saving, investment, and wealth. They are likely to provide greater objectivity to debates on the sustainability of economic development by overcoming the biases of standard indicators with regard to environmental issues.

The proposed national accounting framework, initially restricted to a closed economy, is then generalized to take into account the rest of the world, with the constraint of the additivity of national aggregates to establish “world” aggregates. Each country's output is reduced by the final environmental damage generated by its own activities, including that suffered by the rest of the world. Each country's income and savings are reduced by global environmental damage (generated by its own activities and those of the rest of the world) in proportion to its own exposure to climate change. Crucially, the specificity of cross-border externalities and global public goods is thus addressed precisely in both production flows approach and asset-based approach.

[3] Here, we focus on the integration of environmental assets and the ecosystem services they provide. The proposed methodology could also be applied to the treatment of human capital and intangible assets.

Our approach remains modest: 1) first of all, we refer to the usual national accounts as they are recorded; 2) we propose only to extend the production frontier of goods and services to new - positive or negative - environmental (non-market) services not yet registered, to take them into account in the production process, to value them taking into account their social utility, and to integrate them into the calculation of the usual flow aggregates; 3) on the asset stock side, the asset stock frontier is consistently extended to include new environmental assets, hitherto not taken into account, valued at their social utility. In other words, the objective here is not to reconsider the way in which national accounting describes market activities, but simply to integrate non-market services linked to the quality of the environment and the natural assets that provide them, while respecting the main accounting principles of national accounting (absence of double counting, structure and consistency of accounts, etc.). The expanded aggregates therefore do not mask the usual aggregates but add an environmental component to them. However, this extension of the national accounts leaves the fundamental criticisms on the GDP concept largely unchallenged: it does not claim to measure well-being or sustainability of development, but it can serve as an indicator of equivalent income (see Fleurbaey & Blanchet (2013), Blanchet & Fleurbaey (2022), Blanchet *et al*. (2024)). Given the valuation principles adopted for environmental goods, variations in adjusted GDP at constant prices weight gains in market production and environmental impacts in a way that makes sense in terms of purchasing power of present consumers and of future generations.

The purpose of developing expanded national accounts thus lies in better informing the public about the economic and social challenges posed by polluting production processes, by using adjusted indicators. These indicators do not ignore both the damage caused by our own consumption and the degradation of our natural heritage, and how these factors threaten future development. The building of such accounts also contributes to reflections on the sustainability of our development—in terms of adjusted savings and responsibilities—and provides an adjusted measure of economic growth. Beyond reminding us of these "inconvenient truths," the development of such accounts would also make it possible to objectively report on the efforts made and the benefits obtained, particularly through the implementation of environmental policies, and to inform debates on the challenges of strengthening international climate action, the costs of protection efforts, and the associated benefits.

After reviewing the methodology of Muller *et al*. (2011), Section 1 develops the construction of extended accounts in a closed economy, distinguishing externalities according to the duration of their damage, whether in the present or beyond. Environmental taxation is also introduced into these extended accounts. Section 2 develops the construction of expanded accounts in an open economy, distinguishing between cross-border externalities and global public goods. Finally, Section 3 highlights the contribution of such national accounts, not only to assess the effective growth of our economy and the sustainability of our economic development, but also to study the macroeconomic impacts of the introduction of environmental regulation instruments.

1 – Construction of expanded national accounts in a closed economy

1-1 Review of the methodology of Muller *et al*. (2011)

The approach taken by Muller *et al*. (2011) stems directly from the economic classification of pollution in terms of externalities, as an indirect effect of a production or consumption activity on a utility function, a consumption set, or a production set. Indirect effect means, on the one hand,

that the effect is created by an economic agent other than the one affected and, on the other hand, that it is not offset by a market transaction between the impacting agent and the impacted agent.

Firstly, this definition underlines that these externalities are an integral part of production processes. The approach of Muller *et al.* (2011) thus aimed to both correct the output (and value added) of each industry responsible for air pollution of the negative externalities associated with its production, and at the same time the intermediate consumption and value added of any industry affected by the negative externalities of polluting industries. As these externalities affected not only the market sphere but also various non-market sectors, such as human health and recreational activities, the approach of Muller *et al.* (2011) involves the widening of the classification of activities in national accounting. They propose to incorporate externalities (positive or negative) into national accounts, treating them as flows of services, so that their benefits (or costs) are taken into account in the computation of value added. In other words, it is suggested that additional lines for pollution be added to the existing product balances for goods and services, corresponding to the negative services provided to those who bear the damage.

This approach requires the valuation of these new activities, for which it is not possible to refer to a market transaction, whereas it is the price of such transactions that serves as the basis for the valuation of market goods and services. Following Pigouvian logic, Muller *et al.* (2011) emphasize that, for goods and services whose production is associated with polluting emissions, their market price no longer reflects their value to society, because the cost of the damage associated with these emissions must be deducted from this price (which corresponds only to their value to consumers). The price to be considered for (negatively) valuing pollution is therefore the marginal cost of the associated damage for all the economic agents impacted, i.e., the price they are willing to pay for a marginal effort to reduce pollution. Similarly, the production of positive externalities should be valued by taking as the price the marginal willingness to pay for the service in question, since in this case we are dealing with benefits (+) rather than damages (-).

To illustrate these principles, Box 1 presents a fictional example of expanding the production boundary to include environmental externalities.

Box 1 - Integration of externalities into production accounts and supply and use balances - example of a two-sector (beekeeping and arboriculture) economy

Consider the case of a positive externality associated with the classical example of honey production by the beekeeping sector, an indirect product of which is the production of bees. Honey production is a source of externalities: by increasing the bee population, it has a positive impact on the productivity of arboriculture, which thus benefits from the non-market service of pollination. In the standard national accounts (baseline account), for the beekeeping sector, only the production of honey, which has a value for consumers, is recorded; for the arboriculture sector, the recorded arboricultural production has actually benefited from the positive impacts of the pollination service on its productivity.

Assuming an increase in tree production for an additional unit (marginal benefit) of 2 and an increase in the bee population of 10 units, the benefit associated with pollination services would be 20.

After accounting for bee production and recognizing the associated pollination service in the beekeeping production account, as for a by-product, the production and value added of the beekeeping are increased by +20 (deviation from baseline). Arboriculture production remains unchanged; on the other hand, its intermediate consumption is increased by its use of the pollination service. The value added of arboriculture is reduced by the same amount.

Production account of sectors (deviation from baseline)

Sector	Beekeeping (+pollination service)	Arboriculture (with pollination service)
Production	+20	+0
Intermediate Consumption	+0	+20
Value added	+20	-20

The total gross value added (GDP based on the product approach) remains unchanged in this case. However, its structure between activities is corrected to better reflect the source of value creation.

If bee production is also a source of recreational amenities in the landscape, due to the increase in flowers in the fields in spring, assuming a marginal benefit for hikers of 1, the value added of beekeeping is increased by +30 (in deviation from baseline) and the total gross value added (GDP based on the product approach) is increased by +10 (in deviation from baseline), representing the value of the environmental services provided to hikers.

Production account of sectors (deviation from baseline)

Sector	Beekeeping (+pollination service + recreational amenities)	Arboriculture (with pollination services and recreational amenities)
Production	+20+10	+0
Intermediate Consumption	+0	+20
Value added	+30	-20

We thus add a supply and use balance for environmental services (pollination services and recreational amenities) to the usual national accounts.

Supply and use balance for environmental services (deviation from baseline)

Production Pollination service + recreational amenities	Intermediate Use Pollination service	Final Consumption Recreational amenities
+30	+20	+10

GDP (GDP based on the expenditure approach) is increased by +10 (in deviation from baseline).

1–2 Impacts on future generations and valuation of natural assets

Pollution damages often affect future generations or consist of degradation of natural assets, which will weigh on their development. Conversely, efforts to protect these assets, such as the carbon sink provided by forests, will benefit them. The same type of accounting as above can be applied, the only difference being the nature of the service provided, since the effects mainly affect future dates, or even future generations. Thus, carbon sinks should be accounted for as investments that reduce future damage, thereby improving the "atmosphere capital" (as the opposite of the amount of greenhouse gases in the atmosphere), while CO_2 emissions deteriorate it. Furthermore, when it comes to services that improve or degrade natural heritage, the price to be considered is the present value of the benefits, or the costs of the damage, thus provided at present and future dates.

These valuation principles are consistent with utilitarian approaches to natural capital valuation (see the seminal academic work of Dasgupta & Mäler (2000) and Arrow *et al.* (2003)). The price to be considered corresponds to the implicit price of natural assets. Genuine production and savings defined in a simplified economy incorporate changes in natural assets valued at these prices, providing the basis for expanded national accounts, from production to wealth accounts (see Box 2).

Box 2 - Presentation of a simplified economy with implicit asset prices

Following Dasgupta & Mäler (2000), Mäler *et al.* (2008), Arrow *et al.* (2003), and Arrow *et al.* (2012), we assume a deterministic environment. Let C_τ be a list (vector) of consumer goods and services at time τ, including not only market goods and services, but also everything that can contribute to human well-being: leisure, public goods, environmental amenities, and other non-market services, including those provided by nature.

At time t, there is a projection (at time t) of future consumption vectors. This projection depends on the various asset stocks - productive capital, human capital, and natural capital - $K_t = (\dots, K_{it}, \dots)$ and other state variables at time t (at the beginning of period t) - institutions, technologies, preferences. Let U denote the utility function or net benefits to society derived from

consumption at future date τ. Social welfare V at date t is defined as the sum of future utility flows discounted at the present preference rate δ:

$$V_t = V(K_t) = \sum_{\tau=t}^{\infty} \frac{U(C_\tau)}{(1+\delta)^{\tau-t}}$$

The dynamics of asset variables result from the combination of anthropogenic functions f representing the accumulation, depletion, or degradation (including the depreciation of productive capital) of asset stocks linked to economic and human activities and regeneration processes G. For all i, $K_{it+1} - K_{it} \equiv G^i(K_t) - f^i(K_t, C_t)$.

Where $G^i(K_t)$ is the i-th component of the regeneration function $G(K)$ and $f^i(K_t, C_t)$ is the i-th component of the anthropogenic function $f(K, C)$, both of which are functions of the set of assets K_t.

The implicit price of each asset at time t is then defined by $p_{K_{it}} = p_{K_i}(K_t) \equiv \frac{\partial V(K_t)}{\partial K_{it}}$.

This implicit price of each asset at time t can also be written as $p_{K_{it}} = \sum_{\tau=t}^{\infty} \frac{\frac{\partial U(C_\tau)}{\partial K_{it}}}{(1+\delta)^{\tau-t}}$.

Net savings, also referred to by these authors as genuine savings or comprehensive investment, is then defined as the change in inclusive wealth at basic prices:

$$Net\ Savings_t = (V_{t+1} - V_t)_t = \sum_i p_{K_{it}} . (K_{it+1} - K_{it})$$

- Recording in monetary terms and link to national accounting

In a simplified economy, where consumption is assumed to be aggregated into a single composite good C_t and if we take consumption to be numeraire instead of utility, as national accounting does, the price of each asset at date t becomes:

$$\bar{p}_{K_{it}} = p_{K_{it}}/U'(C_t) \equiv \left. \frac{\partial V(K_t)}{\partial K_{it}} \right/ U'(C_t)$$

The net national product NNP_t - net of the decrease in asset stocks - valued with this numeraire can be defined as:

$$NNP_t = C_t + \sum_i \bar{p}_{K_{it}} . (K_{it+1} - K_{it})$$

NNP_t is such that, for a disturbance in economic equilibrium $(\delta C_t, (\delta(K_{it+1} - K_{it})))$ at t, its variation is equal to that of inclusive wealth measured with this numeraire:

$$\delta V_t/U'(C_t) = \delta C_t + \sum_i \bar{p}_{K_{it}} . \delta(K_{it+1} - K_{it}) = \delta NNP_t$$

- Inclusive wealth and national accounting

If we want to link inclusive wealth and national accounting, we must take into account the distinctions of the latter:

- first, between flow accounts and stock accounts, with saving being the balancing item of flow accounts. Thus, exceptional and unanticipated impacts on assets are recorded below in the balance sheet (stock account);

- then, within flow accounts, for what impacts assets, between $GFCF$ (Gross fixed capital formation) and CCF (Consumption of fixed capital or depreciation), the latter corresponding, for productive capital, to physical deterioration and normal obsolescence.

- Measurement and valuation of different natural assets

In this context, empirical applications for measuring and valuing different natural assets - fisheries, forests, groundwater, atmosphere capital, etc. - have been developed (Mäler *et al*. (2008), Arrow *et al*. (2012, 2013), Fenichel & Abbott (2014), Fenichel *et al*. (2016)). Finally, according to the literature, the assumption of perfect information is relaxed, and uncertainty and risk are introduced at various stages: socio-economic projections, discounting factor, and lastly, calculation of social welfare.

The estimation of the social cost of carbon -the present value of the damage to society caused by an additional ton of CO_2 emissions - is an example of an application that follows this approach. It is based on integrated assessment models (IAMs) of climate change, which generally include a set of projections for population, economic growth, and associated emissions; a set of climate models projecting temperature increases, sea level rise, and greenhouse gas concentrations in the atmosphere, a block of projections of the costs of various damages, and finally a block of projections of the social cost of carbon based on an aggregation and discounting of damage costs. Uncertainty is henceforth introduced from the first block in demographic and growth projections as well as in the discounting factor (see in particular Rennert *et al*. (2022)).

Their approach was developed in the context of debates on indicators of sustainable growth, with its proponents highlighting inclusive or comprehensive wealth as an indicator of sustainability, since economic development, whether optimal or not, is said to be sustainable at the present time if current social (intergenerational) well-being – the present value of future utility flows – does not decline. This criterion has been criticized (see Asheim (2007), Fleurbaey & Blanchet (2013), Fleurbaey (2015)) and alternative proposals[4] have been put forward.

For our purposes here, namely the enlargement of national accounts, without prejudging the indicators that will subsequently be used to assess sustainability, this approach offers a number of advantages, notably that it is consistent with the framework and fundamental principles of national accounting, allowing variations in GDP at constant prices to be interpreted in terms of equivalence of purchasing power (see §1-7 below). Furthermore, social well-being is defined in terms of capital stocks and other state variables - institutions, technologies, preferences, etc. Its change between two time periods is simply expressed as the weighted sum of the changes over all capital stocks valued at implicit prices, i.e. the change in an inclusive wealth indicator which, in national accounting, corresponds to a broad concept of wealth aggregating all asset stocks (productive, human, and natural capital).

[4] Alternative approaches to sustainability are generally based on the "capacity" of future generations to "be as well off" as the present generation (see also Blanchet *et al*. (2024)). Some authors (Pezzey (1997, 2004), Pezzey & Toman (2002)) define sustainability as current welfare being below or equal to the maximum sustainable level (called the "maxi-min value value") or refer to development that is compatible with a "viable" future (Martinet & Doyen (2007), Martinet (2011)). Finally, Fleurbaey (2015) proposes defining sustainability in terms of "leaving it possible for future generations to sustain certain defined targets". He shows that variants of inclusive wealth can serve as indicators of sustainability.

Here, it is applied in discrete time. According to various authors (Mäler *et al*. (2008), World Bank (2006, 2011, 2024), Fleurbaey (2015), Blanchet & Fleurbaey (2020)), this generally allows for a clear distinction between what is done during the current period (production, consumption, accumulation) and what can be done in subsequent periods, given the inherited capital stocks. In theory, the present period can cover a fairly long time: the present generation (with successive or overlapping generations) or a much shorter time such as a year. Discrete time is useful for working with national accounting data, which is generally available on an annual or quarterly basis.

1 – 3 Assumptions and notations

Standard national accounting, which we intend to extend to the environment on the basis of these principles, is summarized by the following equations (written at basic prices) in a closed economy:

$$\begin{cases} Y = VA + ToP = CF + I = R \\ S = Y - CF = R - CF = I \\ \Delta K_{+1} = I - \text{depreciation of fixed capital} + (\text{discoveries} - \text{destructions not related to economic activity}) \\ \qquad\qquad + \text{real revaluation} \end{cases}$$

With the usual notations Y for GDP, VA for the sum of the value added over the sectors, ToP for taxes on products (net of subsidies), CF for final consumption, I for gross productive investment, R for national income, S for national savings, K for capital at the beginning of the period, and Δ representing changes in aggregates, for example $\Delta K_{+1} \equiv K_{+1} - K$.

The first line recalls the three ways of calculating GDP: by production, demand, and income. The last line describes the dynamics of productive capital stock, with the accounting equality between savings and investment bridging the two. These equations can be supplemented to incorporate various extensions of the national accounts (see in particular Heys *et al*. (2024)), as well as the environment.

There are two types of pollution emitted during the production process in industries i: pollution classified as "flow" e_i, which does not degrade the atmosphere beyond the (annual) period considered, and pollution classified as "stock" E_i, which degrades atmosphere capital and other asset stocks (human, productive, natural). We assume a strict partition between the two types of pollution: flow pollution affects only current, final, and intermediate uses; ignoring current damages to intermediate uses, stock pollution degrades asset stocks (see Appendix 1). Obviously, pollution that has both types of impacts can be described by combining these two polar cases.

To simplify the presentation, we assume a single type of flow pollution emission and a single type of stock pollution emission: here, we assume only atmosphere capital KA (included in natural capital).

The corresponding total pollution levels are denoted by e and E, respectively. More generally, lowercase letters are used for flow pollution and uppercase letters for stock pollution. The letter G qualifies adjusted or inclusive aggregates, incorporating environmental impacts.

The purpose of the following sections is to show how the principles set out above, illustrated in highly simplified frameworks, can be used to construct expanded national accounts and to specify the impacts on major economic aggregates.

1-4 Adjusted GDP using the production approach

In line with Box 1, we first reevaluate GDP using the production approach.

Production of flow pollution emissions

First, we correct the production and value added of each industry *i* emitting flow pollution for its impacts on final consumption (new services) and on the intermediate consumption of other industries j.

Let p_j denote the marginal cost of the present damage for industry *j* associated with an additional emission (associated with any industry *i*); p is the marginal cost of damage to final consumption induced by an additional emission of flow pollution from any emitting industry i.

The total costs of damage related to the emission (gross external damage in Muller *et al.*'s terminology) of flow pollution from industry *i* are written as:

$$ged_i = \left(\sum_j p_j + p \right) . e_i$$

Production of stock pollution emissions

We also correct the production and value added of each industry *i* emitting this stock pollution, which only affects atmosphere capital stock.

Let *P* denote the marginal (discounted) cost of present and future damage caused by an additional stock pollution emission from any emitting industry *i.*

The costs of damage related to the emission (gross external damage in Muller *et al.*'s terminology) of stock pollution from industry *i* are:

$$GED_i = P . E_i$$

The expanded production account of any economic activity i should take into account:

- As a negative production: the negative environmental impacts induced to other economic activities $\left(\left(\sum_j p_j\right) . e_i\right)$ and its own non-internalized final environmental damages (consumption of services and atmospheric capital) that it has generated $(p . e_i + P . E_i)$;
- in negative intermediate consumption: the environmental damage it has suffered (and thus the deterioration in its productivity due to the upstream pollution it has received), linked to the activity of other branches $(-p_i . e)$.

The adjusted value added is then written as:

$$GVA_i = VA_i - ged_i - GED_i + p_i . e = VA_i + EVA_i \quad \text{with } EVA_i = -ged_i - GED_i + p_i . e$$

The adjusted value added of each activity i is therefore the sum of its usual value added and its "environmental value added" EVA_i. The latter is negative if the industry pollutes, and positive if

it provides ecosystem services. In the latter case, the services thus provided to other industries are recorded as positive intermediate consumption, whereas pollution-related damage constitutes "negative" services for the industries that suffer it. Figure 1, which describes the input-output table (IOT) and the extended production accounts of this national accounting system, illustrates the way in which its extension is achieved.

Figure 1 – Enlarged Supply and Use Table

	Supply an Use Table	
Supply in **Market Products**	**Intermediate Input Table** **Industries (*j*) (*k*)**	**Final Use Table**
(*l*)	. . . . .	. . .
Environmental Externalities **Pollutions (-) Amenities (+)**		
Pollutions $-ged = -\sum_i ged_i$ $-GED = -\sum_i GED_i$ Amenities	. $-p_j.e$ $-p_k.e$	$-p.e$ $-P.E$

Production Accounts
. . . . . **(*i*)** . . . .
$EVA_i = -ged_i - GED_i - (-p_i.e)$ $GVA_i = VA_i + EVA_i$

By summing over all industries i, we obtain:

$$ged = \left(p + \sum_j p_j\right).e = gedcf + (\sum_j p_j)(\sum_i e_i)$$

where the first term $gedcf = p.e$ corresponds to the valuation of final damage and the second to the sum of the impacts on intermediate uses.

Similarly:

$$GED = P.(\sum_i E_i) = P.E = GEDI$$

By summing over all industries i, the adjusted value added of the economy is written as:

$$GVA = VA - gedcf - GEDI$$

And the adjusted GDP with the production approach:

$$GY = GVA + ToP$$

The aggregate social costs to be deducted from the economy's gross value-added only concern final uses, as the overall impact of productivity losses due to pollution is taken into account in the usual accounts. In fact, the corrections introduced offset each other when the modified value added are aggregated: polluting industries see their estimated value added reduced by the social costs they generate, while polluted industries have their value added credited for the productivity losses they suffer.

This is essential for understanding how gross value added is built up throughout the supply chain, by attributing external costs to the industries that cause pollution (rather than to those that suffer from it), and by crediting those that make efforts to protect the value added they create. However, at the aggregate level, these pollutions of flows between industries do not alter the measurement of the economy's production as a whole, whose value lies in the end uses it enables. For given level of final outputs, the fact that the value added of a firm polluting a river upstream must be measured by deducting the value of the nuisances it causes thus has the counterpart of revaluing the output of firms located downstream, whose low apparent output according to the usual accounts reflects, for example, the implementation of major clean-up expenditure. In this respect, the usual mechanism for aggregating value-added does not lead to a measurement error in GDP. As we shall see below, this is not the case in an open economy, in the presence of transboundary pollution.

1-5 Adjusted GDP using the expenditure approach

Corrections to the calculation of this adjusted GDP are associated with the addition of two supply-use balances. One for the product of flow pollution:

$$ged = \left(p + \sum_j p_j\right).e = gedcf + \left(\sum_j p_j\right)\left(\sum_i e_i\right)$$

The other one for the product of stock pollution:

$$GED = P.(\sum_i E_i) = P.E = GEDI$$

The market aggregates related to final uses (final consumption and investment) are reduced by the value of the damages they suffer.
Hence, adjusted consumption and investment become:

$$\begin{cases} GCF = CF - gedcf = CF - p.e \\ GI = I - GEDI = I - P.E \end{cases}$$

and adjusted GDP in the expenditure approach:

$$GY = Y - gedcf - GEDI$$

As with usual GDP, the two estimates of adjusted GDP - by output or by demand - coincide, as the proposed framework incorporates two new supply and use product lines that are balanced in accounting terms. Thus, this extension of the national accounts, based on the addition of supply and use balances for environmental externalities, makes it possible to define adjusted aggregates with the same properties of absence of double-counting as for the usual aggregates, the construction procedures being identical. In the absence of pollution, the adjusted aggregates coincide with the usual aggregates.

Finally, the valuation assumptions adopted for externalities and natural assets ensure that variations in adjusted GDP at constant prices have the same interpretation in terms of equivalent purchasing power of a representative agent as those of usual GDP: the valuation of market impacts is unchanged; and the relative weight of market and non-market impacts reflects the preferences of end-users, as €1 of environmental damage must be offset by at least €1 of usual GDP to determine an increase in adjusted GDP (at constant prices). The price of pollution reflects the marginal cost of the associated damages, just as the market price reflects the marginal willingness to pay for market goods (see Appendix 2).

1-6 Adjusted income and savings – Consistency of flow and stock accounts

Adjusted income can also be defined by adding to standard primary income any positive or negative income "in kind" distributed without compensation: environmental amenities and pollution damage. Since externalities within the productive structure alter the distribution of production and value added between activities but not the overall value added, these transfers in kind $gedcf$ and $GEDI$ are deducted from the usual national income.

The three definitions of expanded production still coincide, and the adjusted savings derived from them are equal to inclusive investment:

$$\begin{cases} GR = R - gedcf - GEDI = GY \\ GS = GR - GCF = GY - GCF = GI \end{cases}$$

If we turn now to the wealth accounts, the stock of expanded capital should include K_P for produced capital, K_H for human capital, and K_N for natural capital, including atmospheric capital KA. Inclusive wealth at basic price is then equal to $GK = p_{KP}.K_P + p_{KH}.K_H + p_{KN}.K_N$. As we limit ourselves to expanding wealth only to atmosphere capital KA, $GK = p_{KP}.K_P + p_{KA}.KA$

The change in expanded capital at basic prices ΔGK_{+1} must take into account the various factors affecting atmosphere capital: its anthropogenic degradation ($GEDI = P.E$), gas and dust emissions not attributable to economic activity and related to exceptional events (e.g., volcanism) or extreme weather, and the real revaluation of the social cost of carbon (minimal over a one-year horizon) because the marginal cost of damage linked to climate change increases as

long as the accumulation of greenhouse gases in the atmosphere is not stabilized. Emissions E are considered net of carbon sequestration by natural carbon sinks or by capture technologies[5]. Thus, ΔGK_{+1} can be written as[6]:

$$\Delta GK_{+1} = \Delta K_{+1} - GEDI + \text{ non anthrop. impacts} + \text{real revaluation of } KA$$

It should be noted that the change in the expanded stock of wealth at basic price ΔGK_{+1} includes, in addition to the natural wealth component of the inclusive investment ($-GEDI$), two complementary terms, analogous for natural capital to the usual elements of the wealth account (exceptional events and revaluations).

In summary, in a closed economy (i.e., at the global level), by valuing pollution emissions at their marginal social cost, it is possible to integrate pollutant emissions (of flows and stocks) into national accounts. The flow and stock accounts thus constructed are consistent and such that: i) the three approaches to measuring production (adjusted GDP) coincide; ii) the definition of adjusted savings is therefore unambiguous; iii) and its equality with inclusive investment is ensured.

1-7 Taking into account effective pricing of pollutions

In case where externalities are partially internalized through pollution pricing, eco-taxes or permits markets, the total gross damage (ged, GED) must be broken down into: on the one hand, the part borne by polluting industries as a result of this actual price, corresponding to the market value of the distributed permits or the revenue from eco-taxation at its actual marginal price; on the other hand, the residual, referred to as net external damage (ned, NED). Figure 2 below, in which flow pollution is charged at a (marginal) price of τ, illustrates[7] this breakdown and enables us to compare the accounting of polluting goods with that of market goods, in terms of the taxation applied to them.

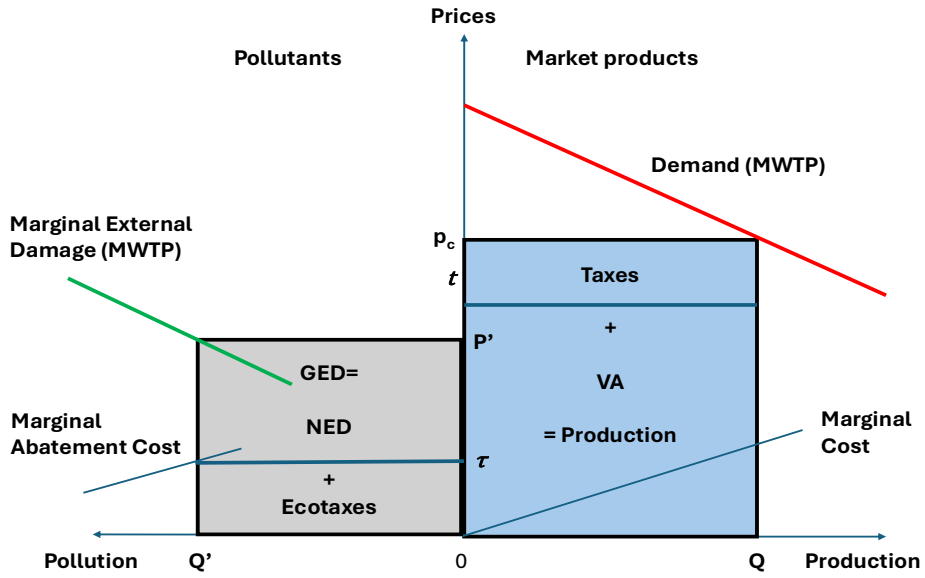
The right-hand side shows the usual accounting for market goods and services and the left-hand side the accounting proposed for pollution. In particular, in the case of a polluting industry, we need to combine the two parts of the figure.

[5] Provided that an appropriate equivalence factor is used for the price of sequestration (see Groom and Venmans (2023), Bureau *et al.* (2025)). However, for the estimate of the social cost of carbon SCC by Rennert *et al.* (2022), the equivalence factor was taken to be equal to 1 as a first approximation.

[6] We assume here that the market prices of stocks of productive assets are equal to their implicit prices.

[7] The aim here is to clarify how eco-taxes are accounted for, without prejudging the impact of effective pollution pricing on emissions, or the way in which this will be reflected in prices, within production chains and then in the final prices of products. These elements can be deduced from observation of the evolution of these accounts in volume and price terms.

Figure 2: Balance of products, market goods and pollution (adapted from Muller *et al.* (2021))



Regarding the impact of taxation, the two sides do not appear symmetrical since, in accounting terms, taxes on market goods are added to VA, while eco-taxes, which also generate revenue, appear as a "negative" rectangle in the figure.

On the market goods side, the production is recorded including taxes. This valuation therefore reflects consumers' marginal willingness to pay for this good (in the absence of rationing). On the pollution side, the gross environmental damage (*GED*) is calculated with reference to the marginal cost of the damage. It corresponds to the product of the quantity of residual emissions with the marginal willingness to pay for depollution.

Under these conditions, the principle for evaluating adjusted GDP by demand ($GY = Y - gedcf - GEDI = GCF + GI$) does not need to be modified in the presence of effective pricing of pollution. However, the valuation of value added must be corrected, as the adjusted value added of polluting activities should only include in negative production the share of social costs they have generated and which have not been monetarily compensated by pricing, i.e. "ned" and "NED". Adjusted production is then reduced by the non-internalized social cost of the associated pollution, and eco-taxes are therefore deducted from adjusted GDP (see Appendix 3).

In the absence of effective pricing, the "ned, NED" are equal to "ged, GED" and we return to the previous analysis for calculating adjusted production using the production approach (see §1-4 above). Conversely, if the effective pricing is equal to the marginal cost of the damage (i.e. in case of Pigouvian pricing which fully internalizes the nuisances), the "ned, NED" are equal to zero and no adjustment would be necessary to correct the value added of the polluting industries concerned.

The specific treatment to be applied to eco-taxes or prices of emission permits, where they exist, compared to the usual treatment of product taxes, can be derived. Assuming that greenhouse gas emissions are priced at T, the adjusted value added of the economy will therefore check:

$$GVA - (\tau.e + T.E) = VA - gedcf - GEDI$$

The equality between the two approaches of GDP, by demand and by production including taxes, can then be written:

$$GY = GCF + GI = GVA + (ToP - (\tau.e + T.E))$$

The pricing of pollution should therefore be deducted from product taxes, as it does not reflect consumers' willingness to pay, but rather a part of the social cost of pollution. Thus, the first correction to be made to national accounts in order to integrate the environment would be to reclassify certain existing taxes directly related to the environment, with production being reduced by these eco-taxes (at unchanged demand prices). This correction would be sufficient if we consider that the effective prices reflect the social cost of pollution. However, as shown in particular by the OECD reviews on actual carbon pricing (see, for example, OECD (2024)), these are generally known to be insufficient to ensure complete internalization. The "non-commoditized" share of gross environmental damage must therefore be deducted of added values of polluting activities.

The income approach, including ecotaxes and adding the environmental revenues distributed in kind ($-gedcf - GEDI$), would also lead to the same adjusted GDP estimates:

$$GR = [VA - (\tau.e + T.E)] + [ToP + (\tau.e + T.E)] - gedcf - GEDI = GY$$

However, the assumption made is that of linear pricing of nuisances. More generally, since the prices to be used to value pollution are their marginal prices, it is the effective marginal pricing rates that determine the split between GED and NED. If the effective pricing is not linear, the value of tax deductibles or free quotas allowances can be interpreted as transfers between the State and the productive sector. This therefore affects the distribution of the expanded national income, but not its overall amount.

In summary, the effective marginal pricing of pollution should be deducted from product taxes as it constitutes a part of the social cost of pollution. The differences between this marginal pricing and its average cost for the various agents, due to free allowances or rebates, should be considered as transfers from the State to the beneficiary agents.

2- Open economy: transboundary pollutions and global public goods

If we consider pollutions without transboundary effects, the above results apply at the level of each country and, by aggregation, for the global economy. Thus, at any scale, the adjustments of economic aggregates to incorporate environment simply involves taking the value of damages to final uses into account.

It is no longer the case with transboundary pollutions or degradations of global commons because their impacts are not associated with monetary compensations or debts, as is the case for the usual trade balance. Accordingly, adjusted national revenue differs from adjusted GDP. In turn, this affects the whole chain of accounts, from value added to inclusive wealth. Moreover, the definition of adjusted savings becomes more complex with cross-border pollutions or shared natural assets, as shown by debates between Hamilton and Clemens (1999), Hamilton (2012) and Arrow *et al.* (2013). Indeed, it depends on whether the focus is on correcting the measurement of production or on the evolution of the national inclusive wealth.

2-1 Understanding the problem to be addressed

To illustrate, let us consider the case of greenhouse gases in a simplified two-country model.

Variables for the rest of the world (ROW) are denoted with star superscripts, and we use the subscript "*w*" for world global aggregates. Hence, global emissions – which determine the evolution of atmospheric capital KA, a common asset – are the sum of the emissions of the country and those of the rest of the world, denoted by E and E^* respectively. Additionally, the social cost of carbon (SCC) can be shared between the discounted marginal cost of future damages for each country resulting from an additional unit of CO_2 in the atmosphere: $SCC = P + P^*$ with $P\ (resp.\ P^*) = (\frac{\partial V}{\partial KA})/U'(C)$.

If we consider the adjusted production of the national country, the adjustment to be done is the same as above: $-SCC.E = -(P + P^*).E$. Just as GDP includes the value of exports and deducts the value of imports, environmental services (positive or negative) provided to or received from the rest of the world must be considered to accurately measure the value added created by each country. The case of a so-called pollution haven, i.e. a site that seeks to attract polluting industries through lighter regulations, knowing that their impacts will extend beyond its jurisdiction, illustrates the issue. Indeed, the genuine production of a pollution haven is not the market value of its products, but the latter minus the cost of the damage caused by its pollution, including to the rest of the world.

However, if we are more concerned with the sustainability of each country's growth, what matters is the overall state of the atmosphere combined with each country's exposure to climate change through its impact on future generations in that country, so: $-P.(E + E^*) = -P.E_w$.

At the world level, the two approaches coincide, the two sums being equal to: $-SCC.E_w = -(P + P^*).(E + E^*)$. But it is not the case at the level of each country, except under assumptions of strict proportionality of the implicit prices to emissions. These are not realistic because some countries are geographically more exposed to the impacts of climate change than others.

2-2 Adjusted production and investment with transboundary effects

The puzzle can be clarified by systematically studying this two-country framework with flow and stock cross-border pollutions. Setting aside pollution pricing to focus on measures of adjusted production and income, the starting point is therefore the simplified representation of the market sphere below:

$$\begin{cases} Y = CF + I + X - M = R \\ S = Y - CF = R - CF = I + X - M \end{cases}$$

In addition to carbon emissions (E,E^*), two types of flow pollutions are introduced for that purpose: the first one (e), originating from the country, affects both its residents (final consumption $gedcf$) and the rest of the world ($gedx$); symmetrically, the country suffers damages from the ROW (e^*), that impact its production conditions (ged^*y) and final consumption (ged^*cf). Corresponding damages are valued as above, with $ged = p.e$; $ged^* = p^*.e^*$ for the gross environmental damages of these two transboundary pollutions.

The only additional principles that we introduce are the following ones:

- a) a territorial approach of emissions: the (negative) production of pollution, valued as above, is accounted for in the country where the process causing it is located. On the

demand side, national emissions therefore affect both final consumption and exports (both negatively). The counterpart of the latter is imported damages of the ROW.

- b) a national valuation of common assets at their implicit price for each country: for example, for CO_2 emissions, these prices correspond to the costs, for each country, of the damage caused by an additional tonne of CO_2, with the sum of these national prices defining the social cost of carbon (SCC).

This is sufficient to expand our adjusted indicators for open economies. Moreover, the associated global accounts reproduce the results of the previous section (see Appendix 4 for calculation details).

First of all, adjusted sum of value added deducts the gross value of all pollutions attributable to the concerned activities. But it also adds the value of damages to national productive processes coming from ROM. So, we have it for the national country:

$$GY = Y - p.e + ged^{*}y - (P + P^{*})E$$

Production and demand approaches for computing this adjusted GDP again provide the same result since the accounts of every environmental service are balanced. At this stage, the main notable point concerns the impact of foreign cross-border pollutions ($ged^{*}y$) affecting the national production process. The underlying logic is similar to that has been seen for production chains at the national level: the value added of the upstream sector is reduced from its environmental damages to the downstream sector that experiences this pollution. And the latter sees its production revised upwards.

But the adjustment related to the degradation of atmospheric capital differs depending on whether the production accounts or the capital accounts are considered. In the first case, the externality logic prevails, leading to deduct from production the environmental damage generated by national production, including that suffered by the ROW: $-(P + P^{*})E$. In the second case, the focus is on the degradation of the common assets, but from the country's inclusive wealth perspective. So, this degradation is valued at its price for the country but includes degradations due to ROW: $GI = I - P(E + E^{*})$.

The sum of the adjustments at the world level finds the results for a closed economy:

$$GI_w - I_w = -(P + P^{*})(E + E^{*}) = GI_w - I_w = -SCC.E_w$$

$$GY_w = Y_w - p.e - p^{*}.e^{*} + ged^{*}y + gedy^{*} - (P + P^{*})(E + E^{*})$$

$$GY_w = Y_w - gedcf - ged^{*}cf - ged^{*}cf^{*} - gedcf^{*} - (P + P^{*})(E + E^{*})$$

2-3 Adjusted national income and savings

By analyzing the associated incomes and savings in this context, one can better understand the differences between the respective adjustments made to the measure of production and to the capital account.

Adjusted national income

Using the previous definition of adjusted income, which adds to the usual primary income the incomes (positive or negative) received "in kind" (valued environmental amenities and pollutions) by each territory, we must therefore deduct from usual national incomes:

- as before, the impacts of local emissions on national final uses ($-gedcf, -P.E$),

- but also, the value of pollution originating from outside the territory ($-ged^*cf, -P.E^*$).

Thus, for the country's adjusted income:

$$GR = R - gedcf - ged^*cf - P.(E + E^*) = GCF + GI + X - M$$

By taking into account only the environmental impacts suffered by the country, but including those originating from outside, this adjusted national income differs from the country's adjusted production. In particular, it includes the damage suffered from cross-border pollution ($ged^*m = ged^*y + ged^*y$). Thus, the balance of environmental services received in kind (EB) complements the usual trade balance:

$$GR = GY + (gedx - ged^*m) + P^*.E - P.E^* = GY - EB$$

$$GBC = X - M + EB$$

This difference between adjusted income and production at the country level reflects the non-market nature of externalities. For transboundary pollutions, the lack of compensation occurs between countries rather than within them, as it was the case in a closed economy: the country does not pay the social cost of the pollution it causes in other countries ($gedx + P^*.E$) but it suffers from foreign uncompensated pollutions ($ged^*m + P.E^*$). As there is no reason for this trade of environmental services in kind to be balanced, we must therefore recognize a dichotomy between the country's adjusted GDP, based on the logic of the sum of value added, and the income thus distributed, either monetary or in kind.

Adjusted savings

Given that in an open economy, the two notions of adjusted production and income no longer coincide, it is necessary to consider two notions of savings:

-the first will consider the sharing of adjusted production between consumption and the formation of inclusive global wealth;

-the second will reflect the share of adjusted national income allocated to improving inclusive national wealth.

Each will be associated as its counterpart to an investment and therefore a variation in inclusive wealth, but referring to different scales of assessment of the sustainability of development.

According to the first perspective, which focuses on the amount of product that is not consumed ($GS^Y = GY - GCF$), the savings indicator would reflect the country's responsibility for its legacy to all future generations, national or foreign ones:

$$GS^Y = [Y - p.e + ged^*y - (P + P^*)E] - [CF - gedcf - ged^*cf]$$

$$GS^Y = S + (ged^*m - gedx) - (P + P^*).E$$

Hence, the whole value of country's CO_2 emissions is deducted from the country's usual savings. The investment associated with this savings indicator therefore concerns global assets, both domestic and foreign. In addition, the social cost of the country's cross-border emissions to ROW is included, net of cross-border emissions suffered by the country from the latter.

Since $GS^Y = GI + GBC = GI - GBC^*$, the sum of these contributions gives the adjusted global savings ($GS^Y + GS^{Y*} = GS^{YW}$). This is not surprising, since the logic of deducting the country's adjusted consumption from its adjusted production, is to measure its contribution to adjusted global savings.

While the above calculation considers the “responsibility” of country’s present agents for the sustainability of global development, adjusted national savings can also be calculated based on the use of national income:

$$GS^R = (R - gedcf - ged^*cf - P.(E + E^*)) - GCF = S - P.(E + E^*)$$

In this case, the adjustment to obtain adjusted national savings reflects the reduction in future inclusive national wealth, the monetary equivalent of the country's future well-being. It is measured by global CO_2 emissions valued at the “national price of CO_2”. The national inclusive wealth account adds this impact, ensuring the link with the country's inclusive investment:

$$GS^R = S + GI - I = GI + BC = GS^Y - EB$$

Then, the following equality reflects that inclusive global investment is the sum of changes in national assets:

$$GS^R + GS^{R*} = GS^{R_w} = GI_w = -((\frac{\partial V}{\partial KA})/U'(C) + (\frac{\partial V^*}{\partial KA})/U^{*\prime}(C^*))(E + E^*)$$

In summary, the results in an open economy, with cross-border pollution and global public goods, highlight that:

- assessments of each country's adjusted GDP (value added created) and adjusted income no longer coincide, as trade of non-market cross-border environmental services is not balanced;

- consequently, the definition of adjusted savings is no longer unambiguous. Savings calculated on the basis of production correspond to the country's contribution to the sustainability of global development,

- ...while savings calculated on the basis of adjusted income are equal to the country's inclusive investment, reflecting the prospects for the sustainability of national development (see numerical application for France, Table 1).

Table 1. Expanded national accounts for France: adjusted aggregates

Economic aggregate	Value 2023 (billions €)	Difference between adjusted and usual aggregates (definition)	Absolute deviation from baseline (billions €)	Relative deviation from baseline
GDP	Y = 2822,5	GY-Y=-(P+P*).E	-59,3	-2.1% of GDP
Trade balance	BC = -56,4	Transboundary pollutions trade (in kind) GBC-BC= EB =-P*.E+P.E*	228,4	- 4.0 x BC
National income	R = 2822,2	GR-R =-P.(E+E*)	-287,7	- 10.2% of R
Net savings	S = 68,0	GS^R-S=-P.(E+E*)	-287,7	- 4,2 x S

Notes: with Net GHG emissions[1]: for France E=339 $MtCO_2$ eq., for World E+E*=*54465* $MtCO_2$ eq.; SCC=P+P*=175 €/t, P=0.03xSCC= 5.25 €/t, P*= 169.75 €/t.

(1) Net emissions: including Land use, land-use change and forestry (LULUCF)

The baseline corresponds to usual aggregates and accounts.

Source: Citepa - Secten (2025); Edgar (2025); French National Accounts in 2023 – base 2020 - Insee; authors' calculations.

In this table, French GDP is reduced by the final environmental damages generated by its own activities, valued at their global cost. National income and net savings of France are reduced by the global environmental damages generated by her own activities and those of the rest of the world, valued at their cost for the country. Thus, it appears that the sustainability of her national development is largely dependent of the environmental damages generated by the activities of the rest of the world.

3 - Issues of expanded accounts

3-1 Macroeconomic impacts of environmental policies

The main motivation for developing new indicators to measure a GDP net of the degradation of environmental assets, adjusted savings, or inclusive investment is to inform debates on the sustainability of growth. The comments in the previous table regarding the inclusion of greenhouse gas emissions in enlarged national accounts for France reflect this perspective. Obviously, this is crucial at a time when scientists are warning of the threats to our development posed by rapid changes in climate, biodiversity, oceans, and water resources.

However, the issue is broader. Since these indicators are built from a general framework of accounts, they can be used at various levels, whether sectoral or relating to the behaviour of economic agents, to inform economic decision-making on environmental policies. Indeed, in the current framework, where only the market costs of these policies are included in the national accounts, environmental protection efforts appear only as losses in productivity or sacrifices in purchasing power. On the other hand, enlarged accounts would also reveal their benefits, thereby

acknowledging the antagonism between the two terms and providing quantitative data expressed in a common metric to inform the associated trade-offs.

In the context of controversies about the impacts of the Clean Air Act, the study by Muller *et al.* (2011) explicitly set this objective. It showed that the increase in "environmental" value added induced by the reduction in negative health impacts thanks to this regulation led to a very positive change in the adjusted production of the US states most affected, despite slower growth in their output as usually measured.

This study focused on the impact on the local pollutants targeted by this regulation: sulphur dioxide, nitrogen oxides, and particulate matter, whose health impacts were valued on the basis of estimates then available for willingness to pay for a marginal reduction in the probability of death (value of a statistical life VSL). As these are local pollutants, the results can therefore be interpreted in the context of the first section, in a closed economy: the so-called environmental value added corresponds to the difference between adjusted production and usual production, at the activity level or at the global level ($EVA_i = GVA_i - VA_i;\ EY = GY - Y$).

The observation that considering environmental value added can change – either negatively or positively– the assessment of the structure and development of an activity can be replicated. In the case of French forests, for example, the environmental services to be considered are diverse: carbon sequestration, regulatory services, recreational amenities, and others. The adjusted value added of the forestry and wood sector would therefore amount to 3.5 times its market value added. Moreover, the decline in carbon sinks appears to be a key factor in the evolution of this adjusted value added over the past ten years (Bureau *et al.*, 2025). These two studies highlight how incomplete (or biased) standard measures of production are, compared to the broader indicators proposed here for measuring it.

Although conducted in the context of debates over particular environmental policies, these studies do not go as far as providing assessments of their effectiveness, as other factors may have influenced the observed changes in value added and pollution. However, it must be noted that if it were possible to isolate and attribute the corresponding effects, the resulting changes in the enlarged national accounts at basic prices would provide information on this effectiveness.

To precise this idea, let us consider a regulation of local pollution flows that reduces emissions ($\delta e < 0$), at the price of a decrease in usual GDP at constant prices ($\delta Y < 0$) due to the costs incurred to achieve this reduction. Hence, we observe an apparent decrease in the productivity of the economy as measured by standard indicators, which can therefore be interpreted as a macroeconomic abatement cost. The change in adjusted value added at initial prices (including the implicit value of pollution p) would therefore be (see Appendix 2):

$$\delta GY = \delta Y - p.\delta e = \delta Y + \delta EY$$

Thus, adjusted GDP can be used to compare the costs and benefits of the environmental policies implemented, at the macroeconomic level. Obviously, these do not replace specific assessments for each instrument, which are necessary to optimize them. However, they would provide a basis for the evaluation of policies that remain controversial, as noted by Muller *et al.* (2011), and would ensure consistency between these assessments and macroeconomic analysis.

Looking at climate cooperation impacts allows to go further, by highlighting the importance of previous sections concerning open economies.

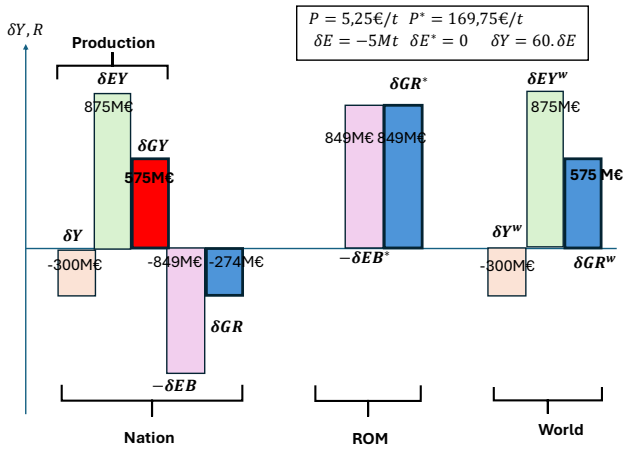
3-2 Economics of international cooperation

From this perspective, we can analyze the impact of strengthening national policy to reduce CO_2 emissions ($\delta E < 0$). Denoting again the macroeconomic abatement cost δY (< 0) and using table 1 figures regarding the social costs of carbon, the impact on the country's adjusted GDP is as follows:

$$\delta GY = \delta Y - (P + P^*).\delta E = \delta Y - SCC.\delta E$$

It will be highly favourable if the social cost of carbon exceeds the unit abatement cost, as shown in Figure 3. This illustrates the situation for a marginal effort at the French level ($\delta E = -5Mt\ CO_2$)[8], assuming a marginal abatement cost of 60€/t CO_2, consistent with the level of effective carbon pricing.

Figure 3: Impacts of a unilateral reduction of CO_2 emissions



However, this increase in adjusted GDP mainly benefits the rest of the world, whose adjusted income increases as $\delta GR^* = \delta EB = P^*\delta E$. On the other hand, in terms of what matters at the country's level – namely, adjusted income – the balance is unfavourable. Figure 3 then illustrates the basics of climate economics (see, for example, Nordhaus, 2015): it is not in a country's interest to make efforts whose cost would exceed the direct benefits it would receive, but rather to act as a free rider, relying on the efforts of others. To overcome this inaction, cooperation is needed to ensure compensation or reciprocity of efforts ($\delta E, \delta E^*$) and their fair distribution. The impacts on expanded national accounts would then be as follows:

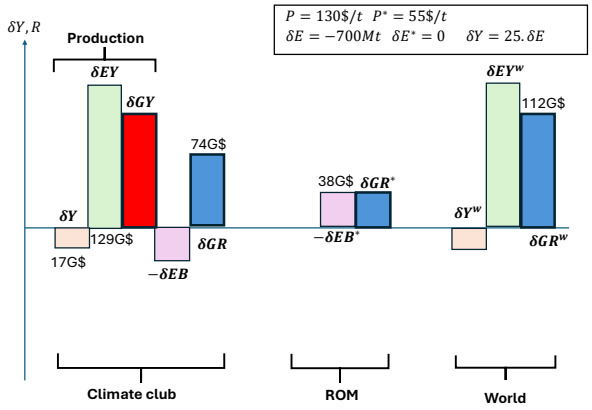
$$\begin{cases} \delta GR = \delta Y - P.\delta(E + E^*) \\ \delta GR^* = \delta Y^* - P^*.\delta(E + E^*) \\ \delta GY_w = \delta GR + \delta GR^* = -SCC.\delta(E + E^*) + \delta Y + \delta Y^* \end{cases}$$

For example, drawing on the approach of Cramton *et al.* (2015), the Harvard-MIT Global Climate Policy Project (2025) proposes implementing minimum carbon pricing rates of approximately 50$/$t$ CO_2 in the highest-emitting sectors, as part of a broad coalition covering about 80% of global

[8] This represents - 1.4% (- 1.5%) of gross (net) emissions in 2023.

emissions[9]. Assuming the initial level of effort is generally low, the average cost would be about half this ceiling price. The impact of increased cooperative efforts[10] to reduce CO_2 emissions on expanded national accounts could then become (see Figure 4):

Figure 4: Impacts of cooperative climate policies (GCPP, Harvard – MIT, 2025)



Conclusion

To better inform public debates on the sustainability of economic development and environmental policies, the accounting framework developed here first reiterates the findings of Muller *et al.* (2011) on integrating environmental damage into national accounts, and those of Dasgupta (2021) concerning the valuation of damage to natural assets.

Moreover, this framework serves as a reference for reminding various technical aspects useful for implementation. For example, the aggregate social costs to be deducted from the economy's value added concern only final uses, as the overall impact of productivity losses due to pollution is already internalised in standard accounts. Additionally, the effective marginal pricing of pollution should be deducted from product taxes, as it forms part of the social cost of pollution. But these results are obtained here without assuming competitive markets.

Above all, the results for open economies, incorporating cross-border pollutions and global public goods such as climate, highlight that country's adjusted GDP and adjusted income no longer coincide when trade of environmental non marketed services is not balanced. Accordingly, a distinction must be made between two concepts of adjusted savings, depending on whether the focus is on the country's contribution to the sustainability of global development or on the prospects for the sustainability of national development.

The implementation of such framework would allow to illustrate the national and international macroeconomic impacts of different environmental policies, what is not possible within the usual system of national accounts. Beyond greenhouse gases emissions, other global common natural assets, such as the ocean and the high seas, biodiversity, or even other forms of non-marketed capital such like educational capital as part of human heritage could be integrated. And this would

[9] The steel, aluminium, cement, and fertiliser sectors form a broad coalition that includes, in addition to the EU, the UK, and ETS countries, major emitting countries likely to become “first movers” such as Australia, Brazil, Canada, China, India, Indonesia, and Thailand, as well as a bloc of African countries producing these products, including Algeria, Cameroon, Egypt, Ghana, Kenya, Mozambique, Togo, Uganda, and Zambia.
[10] $\delta E =$ -700 $Mt\mathrm{CO}_2$ would correspond to approximately - 1.7% of the gross emissions of this broad coalition.

be useful to account for the macroeconomic impacts of policies to protect the high seas (in particular the High Seas Treaty, which will enter into force in January 2026), or international spillovers of policies to attract foreign researchers, or more broadly, immigration policies.

Appendix 1 - Air pollution – Stochastic modeling

There are two types of pollutants:

- non-persistent pollutants, which have a lifespan of no more than 2-3 years, such as particulate matter, nitrogen oxide (NO_x), sulfur dioxide (SO_2), ammonia, and volatile organic compounds;
- and persistent pollutants linked to greenhouse gases (carbon dioxide CO_2, methane CH_4, and nitrous oxide N_2O); this pollution degrades atmospheric capital and other asset stocks.

We assume that each industry i emits air pollution ET_{it} during period t, which is a weighted sum of two types of pollutants: a short-term transitory pollution e_{it} lasting no more than one year, and a medium-long-run pollution E_{it} lasting longer.

In a stochastic model, the transitory component e_{it} can be represented by a stationary random process $I(0)$, as a white noise type around a constant mean; it is assumed to have a negative impact on various types of consumption (e.g., recreational services) but no impact on atmospheric capital in the chosen (annual) frequency, nor, for simplicity, on other asset stocks (human capital, productive capital, and other natural asset stocks).

The medium-long-run component E_{it} includes both the non-transitory component, which lasts 2-3 years, of the so-called non-persistent pollution, and the component related to greenhouse gas pollution. It can be represented by a random process $I(1)$, a low-frequency random walk, with a local drift ME_{it} (an AR(1) process summarizing the 2–3-year persistence of the so-called non-persistent pollution). This pollution has a negative impact on atmospheric capital and other asset stocks (human capital, productive capital, and other natural asset stocks) through the anthropogenic function f.

Air pollution ET_{it} related to industry i at time t can therefore be expressed as:

$$ET_{it} = (1 - \alpha_{it}).\, e_{it} + \alpha_{it}.\, E_{it}$$

with $e_{it} \sim I(0)$ with mean me_i and variance $\sigma^2_{e_i}$ and $E_{it} \sim I(1)$, a random walk at low frequency with local drift:

$\Delta E_{it} = ME_{it} + \Delta a_{it}$ where Δa_{it} is $I(0)$, with mean zero and variance $\sigma^2_{a_i}$, is uncorrelated with ME_{it} over low frequencies

ME_{it} is modeled as an AR(1) process, with mean μ_{ME_i} and an AR parameter ρ_{ME_i}, whose half-life h is the solution to $\rho^h_{ME_i}$ =1/2. For example, for $h = 1.5,\ \rho_{ME_i} = 0.71$.

$ME_{it} = \left(1 - \rho_{ME_i}\right).\, \mu_{ME_i} + \rho_{ME_i}.\, ME_{it-1} + u_{it}$

where $u_{it} \sim I(0)$with mean 0 and variance $\sigma^2_{u_i}$.

Appendix 2 - Interpreting changes in adjusted GDP at constant prices

We note $((x_l), e)$ the vector of final consumption and flow pollution, (K_P, K_A) the two components of inclusive wealth (productive capital and atmospheric capital), and $((p_l),\ p, p_{KP}, P)$ the corresponding prices in the reference situation (baseline). For a marginal disturbance in the economy in the neighborhood of the latter, the variation in adjusted GDP at constant prices can be deduced from the demand approach:

$$\delta GY = \sum_l p_l . \delta x_l + p_{KP} . \delta(K_{P+1} - K_P) - p . \delta e - P . \delta E$$

It is assumed that final consumption can be associated with the utility $(U(\ (x_l), e)$ of a "representative agent" whose demands for market goods (x_l) are satisfied, and that $V(K_p, K_A)$ represents the social welfare associated with the state of assets available for future development, total welfare being the sum of these two components. Noting U'_C the marginal utility with respect to the representative agent's aggregated consumption, we can write:

$$\begin{cases} \forall l, \quad p_l = (\dfrac{\partial U}{\partial x_l})/U'_C \\ p = -(\dfrac{\partial U}{\partial e})/U'_C \\ p_{KP} = -(\dfrac{\partial V}{\partial K_{KP}})/U'_C \\ P = -(\partial V/\partial K_A)/U'_C \end{cases}$$

We deduce:

$$\sum_l p_l . \delta x_l - p . \delta e = \delta U/U'_C$$

This first term of the variation in adjusted GDP at constant prices can therefore be interpreted as a variation in adjusted purchasing power, a variation in the associated utility expressed in terms of present aggregated consumption.

Similarly, the deterioration in atmospheric capital $-P . \delta E$ can be interpreted as a component of a variation of inclusive wealth, expressed in terms of present aggregated consumption (see Box 2).

Apppendix 3 - Taking into account effective pricing of pollution

Assuming that flow pollution emissions are charged at a (marginal) price of τ, and that greenhouse gas emissions are charged at a price of T, we then have for each industry i:

$$\begin{cases} ned_i = \left(p + \sum_j p_j - \tau \right) . e_i \\ NED_i = (P - T) . E_i \end{cases}$$

Its adjusted value added is therefore written as:

$$GVA_i = VA_i - ned_i - NED_i + p_i . e$$

And, using the same summation as in §1-4, we obtain the adjusted value added of the economy:

$$GVA - (\tau . e + T . E) = VA - gedcf - GEDI$$

Appendix 4 – Adjusted aggregates for an open economy with transboundary flows and climate

The indices in superscript indicate in order: the issuing country, with star for emissions of flows coming from the rest of the world (e.g., ged^*); then the aggregate considered (e.g., $cf\ vs\ cf^*$). The accounts corresponding to the two cross-border pollutions thus verify:

$$p.e - gedcf = gedx = gedcf^* + gedy^* = gedm^*$$

$$p^*.e^* - ged^*cf^* = ged^*x^* = ged^*cf + ged^*y = ged^*m$$

The balance of resources and uses of the country is thus modified, by adding the following lines:

Y	CF	I	X	-M
-p.e	*-gedcf*		*-gedx*	
*ged*y*	*-ged*cf*			ged^*m
-(P+P).E*		*-P.E*	*-P*.E*	
		*-P.E**		*P.E**

By summing the lines, we obtain the adjusted indicators of this economy:

$$GY = Y - p.e + ged^*y - (P + P^*)E$$

$$GCF = CF - gedcf - ged^*cf$$

$$GI = I - P(E + E^*)$$

And for the trade balance of in kind environmental services (EB):

$$EB = -gedx + ged^*m - P^*E + PE^* = -EB^*$$

The adjusted trade balance follows:

$$GBC = X - M + EB = -GBC^*$$

And we have then for the demand approach of GDP:

$$GY = GCF + GI + GBC$$

Results being similar for ROW, adjusted final consumption and investment at the global level are:

$$GCF_w = CF_w - gedcf - ged^*cf - ged^*cf^* - gedcf^*$$

$$GI_w = I_w - (P + P^*)(E + E^*)$$

The global GDP is therefore worth (production approach):

$$GY_w = GY + GY^* = Y_w - p.e - p^*.e^* + ged^*y + gedy^* - (P + P^*)(E + E^*)$$

Or (demand approach) :

$$GY_w = GCF_w + GI_w = Y_w - gedcf - ged^*cf - ged^*cf^* - gedcf^* - (P + P^*)(E + E^*)$$

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IN ECONOMICS AND STATISTICS

CREST
Center for Research in Economics and Statistics
UMR 9194

5 Avenue Henry Le Chatelier
TSA 96642
91764 Palaiseau Cedex
FRANCE

Phone: +33 (0)1 70 26 67 00
Email: info@crest.science
https://crest.science/

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