Green Domestic Product

Methodological Report

Technical Appendix

E4S Technical Report
2022

Green Domestic Product: Methodological Report

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MOTIVATION

The Gross Domestic Product (GDP) is a valuable indicator measuring the monetary value of all goods and services produced in a country within a given time period. But in a world of pervasive externalities, the GDP is not a good measure of the value effectively created because it fails to account for the indirect costs and benefits that arise due to our economic activities. In this report, we propose a novel indicator, the Green Domestic Product (GrDP), to remedy some of these shortcomings.

The GrDP extends the scope of the GDP to integrate the depletion of natural, social, and human capital. By assessing the effects of specific pollutants on infrastructure, human health, environment, and ecosystems, we can determine the costs of production that are not considered in the traditional GDP framework.

Although the concept of GrDP is easy to grasp, measuring externalities is challenging. In this report, we detail the methodology and assumptions behind the current version of GrDP. First, we define the scope of pollutants and impacts considered. Then, we detail the assumptions used to value the external costs and to calculate GrDP. Finally, we discuss the limitations of the GrDP in its current form.

POLLUTANTS AND IMPACTS CONSIDERED

In its current version, the GrDP only includes the external costs for which the impacts are known, measured, and priced. Three groups of pollutants and their externalities satisfy these criteria: greenhouse gases (GHGs), air pollutants, and heavy metals.

Greenhouse gases

GHGs are responsible for climate change, which has a wide range of negative impacts on human society and ecosystems by altering temperature and precipitation patterns. Climate change impacts include a decrease in economic and agricultural productivity due to more frequent heatwaves and droughts, the destruction of manufactured capital due to extreme events, and biodiversity loss.

Most economic activities contribute to the emission of GHGs. Carbon dioxide (CO_2) is released during the combustion of fossil fuels for electricity-generation, heating, and transport. Methane (CH_4) is released by livestock, fossil fuel production and use (e.g., leakage), and waste treatment processes. The fertilisation of land leads to the emission of nitrous oxide (N_2O). Fluorinated gases (HFC, PFC, SF_6) are produced during industrial processes. Finally, land-use changes such as deforestation or the destruction of wetlands decrease the carbon absorbed by ecosystems. We consider all the above mentioned GHGs in this study, i.e., CO_2, CH_4, N_2O, and HFC/PFC/SF_6.

There exists three main GHG emissions reporting methods:

1. **National Emission Inventory** follows the Intergovernmental Panel on Climate Change (IPCC) guidelines and is used as a basis for setting GHGs reduction targets in the context of international agreements such as the Kyoto Protocol and the Paris Agreement. This reporting, required annually by the United Nations Framework Convention on Climate Change (UNFCCC), relies on a territorial principle: it inventories all emissions from residents and non-residents inside a country. The reporting can be adjusted to include emissions from international transport (e.g., aviation) and from Land Use, Land Use Change, and Forestry (LULUCF).
2. **Air Emission Accounts (AEA)**, based on the Systems of Environmental and Economic Accounts (SEEA) approach, considers a residential principle: it includes all emissions resulting from the activities of a country's residents, including the ones abroad.
3. **GHG footprint** complements the AEA approach by integrating the emissions generated by the production of imported goods and services and excluding the ones due to exports. The inventory of GHG footprint emissions do not (yet) follow an international protocol but are estimated using Input-Output Tables (IOT), i.e., economic reporting of all sales and purchases between producers and consumers – including imports and exports.

The three reporting methods differ based on their scope. To take an example, emissions of foreign tourists driving in Switzerland will be included in the Swiss UNFCCC reporting, but not in the AEA. Emissions of Swiss tourists driving abroad will be accounted for in the AEA but not in UNFCCC. Finally, the emissions caused by the production of an imported vehicle in Switzerland would not be considered in the Swiss UNFCCC and AEA reporting – they would be in the country of production – but they are included within the GHG footprint.

Air pollutants and heavy metals

Fossil-fuel combustion and industrial and agricultural processes also emit various air pollutants. Once in the atmosphere, the pollutants can be directly inhaled by humans. They can also react with the environment, creating new harmful substances. Finally, they can contaminate water and soils, and then be ingested by ecosystems and in turn by humans. The pollutants considered in this study are:

- **"main" air pollutants**: particulate matter ($PM_{2.5}$ and PM_{10}), sulphur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOC),
- **heavy metals**: arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni).

The main air pollutants act as precursors to the creation of $PM_{2.5}$, NO_2, and ozone (O_3). Human exposure to these substances leads to various respiratory and cardiovascular diseases (e.g., asthma and bronchitis) and excess mortality. Similarly, heavy metals exposure is a cause of health issues such as cancer, diabetes, respiratory and cardiovascular diseases. Lead and mercury can also be responsible for IQ loss.

The impacts are not restricted to human health though. Ozone exposure decreases crops' yields and biomass production in forests. NO_x and SO_2 damages buildings by degrading stone and metalwork. NO_x and NH_3 affect ecosystems by modifying the nitrogen balance due to eutrophication.

The detailed impacts considered in this study are reported in **Table 2**. The scope follows the one of the European Environment Agency (EEA) report Costs of air pollution from European industrial facilities 2008–2017 (2021) by the European Topic Centre on Air pollution, transport, noise and industrial pollution (ETC/ATNI).[1] Indeed, at the time of this study, the ETC/ATNI report offers the most up-to-date assessment of the costs of air pollutants, with a broad scope of impacts and European countries considered.

As for GHGs, the inventory of air pollutants emissions can either follow a territorial principle – National Emission Inventory – or a resident principle – Air Emissions Accounts. We collect the data from Eurostat (see **Table 1**). However, air pollutant "footprint" emissions are not (yet) included in this study due to the lack of reliable estimation.

Table 1 - GHG emissions reporting

Reporting	**National Inventory**	**Air Emissions Accounts**	**GHG Footprint**
Guidelines	IPCC	SEEA	SEEA + IOT
Principle	Territorial	Residential	Residential
Data source	EU: EUROSTAT ENV_AIR (EEA) CH: FOEN	EU: EUROSTAT ENV_AC CH: FSO	EU: GCP CH: FSO
Scope			
Emissions of **residents** emitted **abroad**	No	Yes	Yes
Emissions of **non-residents**	Yes	No	No
Emissions due to **imports** of goods and services	No	No	Yes
Emissions due to **exports** of goods and services	Yes	Yes	No

1 Schucht, S., Real, E., Létinois, L., Colette, A., Holland, M., Spadaro, J., Opie, L., Brook, R., Garland, L. and Gibbs, M. (2021). Costs of air pollution from European industrial facilities 2008–2017. European Topic Centre on Air pollution, transport, noise and industrial pollution (ETC/ATNI).

Table 2 - Scope of impacts quantified

Category	Exposure	Impact
Human capital – Health	Human exposure to $PM_{2.5}$	Mortality Bronchitis Respiratory hospital admissions Cardiac hospital admissions Restricted activity days Lost working days
	Human exposure to O_3	Mortality Respiratory hospital admissions Cardiac hospital admissions Minor restricted activity days
	Human exposure to NO_2	Mortality Bronchitis Respiratory hospital admissions
	Human exposure to arsenic	All-cause mortality Non cancer mortality Cancer mortality Non-fatal cancers Chronic bronchitis IQ loss Diabetes
	Human exposure to cadmium	All-cause mortality Cancer mortality Non-fatal cancers Osteoporosis (hip fractures)
	Human exposure to lead	All-cause mortality IQ loss
	Human exposure to mercury	Cardiovascular mortality IQ loss Anaemia
	Human exposure to nickel	Cancer mortality Non-fatal cancers
Environmental capital	Exposure of crops to O_3	Yield loss for 121 crops
	Exposure of forests to O_3	Loss in total biomass production for coniferous and deciduous trees
	Exposure of ecosystems to eutrophication from total deposition of nitrogen (dry and wet, oxidised and reduced nitrogen) due to emissions of NO_x and NH_3	Ecosystems damage in Natura 2000 areas
Physical capital	Exposure of utilitarian buildings to NO_x and SO_2	Degradation of stone and metalwork, particularly zinc, galvanised steel

HOW TO QUANTIFY AND VALUE EXTERNALITIES?

Overview of existing methods

The Impact Pathway Approach (IPA) framework allows us to quantify and value externalities. In short, it involves five steps:

1. Quantify the pollutant emissions resulting from human activities,
2. Model the dispersion of pollution around the source and its chemical transformation in the environment,
3. Quantify the exposure of the population (human or ecosystems) to changes in the concentration of pollutants,
4. Estimate the impacts associated to a change in the exposure,
5. Calculate the monetary equivalent of each impact.

Several methods were developed to convert the externalities into monetary terms:

1. Avoidance costs are the costs to prevent externalities by avoiding the release of an additional unit of pollutant.
2. Damage costs are the costs incurred by the pollution, for example agricultural production loss due to a decrease in crop yields.
3. Abatement costs are a type of damage cost, they are the costs of reversing the damages caused by the pollution, such as health expenditures to treat diseases.

Air pollutants and heavy metals

The valuation of the externalities due to air pollutants and heavy metals rely on the damage cost approach. Valuing externalities sometimes requires pricing the priceless, e.g., excess mortality. Although this might raise ethical questions, the alternative – i.e., not accounting for such impacts – is arguably worse. One way to value mortality is the value of statistical life (VSL), which measures how much people are willing to pay for a reduction in their risk of dying from adverse health conditions. Another is the value of life-year (VOLY), which estimates the damage costs based upon the loss of life expectancy, expressed as potential years of life lost and accounting for the age at which deaths occur. VOLY provides a lower estimate than VSL for health damages.

Tables 3, **4**, and **5** detail the unit damage costs or air pollutants and heavy metals used in this study, as well as the countries considered. As mentioned above, data is taken from the 2021 ETC/ATNI report Costs of air pollution from European industrial facilities 2008–2017 (2021). The damage costs of air pollutants vary for each country due to geographical and socio-economic factors. For example, the topography influences the dispersion of pollutants while the density of population and localisation of the sources of pollution impact human exposure. The damage costs also include transboundary effects, i.e., they cover the impacts perceived in the emitter country and the impacts perceived in other countries.

For some countries, the damage costs of the impacts on crops and forests from ozone due to NOx emissions are negative (see for example, the Netherlands and Belgium) – i.e., a reduction of NOx emissions increases the impacts – due to the titration effect. The titration effect consists of the removal of ozone due to relatively high NO_x concentration compared to VOC concentration. A reduction of NO_x emissions in those areas decreases the ambient NO_x concentration and can neutralize the titration effect, leading to an increase in ozone concentration.

Greenhouse gases

For GHGs, we rely on avoidance costs. Quantifying the impacts of climate change is prone to significant uncertainties and depends on the scenarios of the future. As such, the calculated values for the social cost of carbon in the literature varies from a few euros – or could even be negative – to several thousand euros per ton of CO_2. The implicit assumption behind using avoidance cost for GHGs is that externalities are prevented, i.e., global temperature rise is limited to 1.5-2°C above pre-industrial levels by reaching net zero by 2050.

To account for uncertainties in the cost of carbon, we estimate the external costs with three values, obtained from the European Commission report Handbook on the external costs of transport (2020): low (63 €2019/

Table 3 - Damage costs of air pollutants: Impact on health, in €2019 per tonne of emissions of precursors

Harmful substance	Impact on health from fine particulate matter $PM_{2.5}$ and ozone O_3												Impact on health from NO_2	
Precursor	NO_x		$PM_{2.5}$		PM_{10}		SO_2		VOC		NH_3		NO_x	
Method	VOLY	VSL	VOLY	VSL	VOLY	VSL	VOLY	VSL	VOLY	VSL	VOLY	VSL	VOLY	VSL
Belgium	13'143	43'697	159'127	512'037	103'329	332'491	48'642	158'596	2'534	7'784	49'903	162'757	6'194	23'567
Bulgaria	8'176	24'849	82'132	309'647	53'333	201'070	14'813	46'067	951	2'735	16'472	57'968	3'212	14'273
Czechia	10'470	33'768	88'092	282'451	57'202	183'409	21'809	70'558	2'569	7'994	41'050	131'597	3'916	14'679
Denmark	4'900	15'790	39'174	124'113	25'437	80'593	16'926	53'926	495	1'429	8'030	25'429	2'499	9'286
Germany	13'211	44'736	75'797	266'647	49'219	173'147	33'985	115'821	1'809	5'540	26'428	90'380	6'886	29'526
Estonia	811	2'482	7'941	26'735	5'157	17'360	2'105	6'652	172	478	3'702	12'426	1'078	4'296
Ireland	7'907	23'601	19'612	50'219	12'735	32'609	26'740	77'829	595	1'739	5'115	15'412	2'397	5'973
Greece	1'973	5'045	41'820	145'705	27'156	94'614	11'773	36'422	1'189	3'396	11'940	40'964	5'044	21'290
Spain	5'448	17'013	63'795	201'671	41'425	130'955	22'484	71'851	1'184	3'496	7'116	22'620	6'452	24'376
France	12'947	41'221	65'395	208'191	42'464	135'189	34'225	110'898	1'981	6'034	13'167	42'289	5'771	21'650
Croatia	12'633	41'877	54'289	192'306	35'252	124'874	22'942	78'640	1'624	5'119	17'409	59'766	3'928	16'943
Italy	19'257	68'375	165'372	592'650	107'384	384'838	26'774	93'561	4'568	15'406	25'980	92'536	8'964	39'045
Cyprus	3'841	6'803	22'448	48'390	14'576	31'422	10'153	17'838	524	851	6'621	14'690	3'023	7'947
Latvia	1'399	4'505	26'831	98'627	17'423	64'043	8'096	28'519	224	627	4'742	16'887	3'340	14'358
Lithuania	2'125	6'807	17'633	62'144	11'450	40'353	7'575	25'328	224	609	5'888	20'409	2'733	11'227
Luxembourg	16'366	54'384	80'297	247'472	52'141	160'696	45'317	149'590	1'478	4'477	25'404	82'699	5'101	17'133
Hungary	12'384	39'822	77'977	261'548	50'635	169'836	23'636	76'953	1'539	4'714	22'556	74'032	7'059	28'094
Malta	66	998	52'496	150'194	34'088	97'529	5'401	16'703	848	2'433	30'502	87'032	1'783	5'992
Netherlands	14'428	48'586	95'143	294'599	61'781	191'298	41'868	135'101	1'935	5'918	34'773	112'094	8'620	30'728
Austria	16'187	53'751	69'268	227'195	44'979	147'529	34'115	112'608	2'528	8'094	22'838	75'210	5'489	21'037
Poland	4'241	13'181	42'634	129'265	27'684	83'938	13'572	41'882	1'026	2'958	22'895	70'230	3'837	13'351
Portugal	3'660	11'986	67'543	234'012	43'859	151'956	10'506	35'235	709	2'128	7'339	25'279	4'524	18'794
Romania	10'147	32'035	64'723	217'324	42'028	141'119	19'532	61'292	1'246	3'685	14'949	48'566	4'922	19'594
Slovenia	18'908	63'747	112'372	373'078	72'969	242'259	27'745	93'029	3'050	9'934	23'949	80'286	5'052	19'660
Slovakia	10'327	32'141	76'992	233'434	49'995	151'580	19'286	59'894	1'862	5'657	33'896	104'013	5'113	17'254
Finland	975	2'998	20'346	65'365	13'212	42'445	5'286	16'997	210	603	4'185	13'494	2'962	11'296
Sweden	2'045	6'307	16'854	53'538	10'944	34'765	6'298	20'025	312	899	5'456	17'332	3'176	12'056
Norway	1'616	4'852	20'096	56'741	13'049	36'845	5'082	15'339	377	1'072	3'332	9'673	3'616	11'746
Switzerland	30'633	96'937	101'182	306'655	65'703	199'126	74'294	231'497	3'882	12'056	20'629	64'689	12'696	45'006
United Kingdom	9'628	30'821	86'815	268'250	56'373	174'188	37'445	117'145	1'552	4'614	32'816	102'432	6'797	24'650
Turkey	6'628	11'089	61'497	99'897	39'933	64'868	15'484	25'939	1'139	1'884	15'691	25'728	12'592	22'207

Table 4 - Damage costs of air pollutants: other impacts, in €2019 per tonne of emissions of precursors

Impact	Impact on crops from ozone O_3		Impact on forests from ozone O_3		Impacts on buildings		Impacts on ecosystems (eutrophication)	
Precursor	NO_x	NMVOC	NO_x	NMVOC	NO_x	SO_2	NH_3	NO_x
Belgium	12	121	-5	48	119	679	44	37
Bulgaria	398	47	94	9	131	301	138	25
Czechia	337	108	112	36	183	719	102	39
Denmark	56	35	39	19	102	348	95	47
Germany	162	132	49	48	138	636	168	77
Estonia	75	22	48	8	45	137	2'594	170
Ireland	93	25	65	15	48	105	220	75
Greece	217	79	17	5	71	128	165	30
Spain	533	91	128	24	26	64	186	59
France	389	122	186	53	103	354	299	106
Croatia	593	80	241	32	102	373	148	77
Italy	419	169	134	67	82	193	490	150
Cyprus	273	38	1	0	102	373	0	0
Latvia	95	28	64	10	67	180	213	87
Lithuania	127	29	66	9	107	270	151	65
Luxembourg	207	117	52	46	150	629	77	31
Hungary	495	61	154	20	256	681	284	100
Malta	51	37	15	16	102	373	0	0
Netherlands	-53	94	-26	39	120	652	62	45
Austria	485	94	172	38	208	516	403	128
Poland	142	85	46	27	191	716	376	100
Portugal	422	62	179	31	19	49	82	31
Romania	360	45	173	18	198	539	96	52
Slovenia	521	132	223	61	185	480	115	70
Slovakia	400	73	142	23	235	677	296	134
Finland	78	22	57	9	29	107	155	62
Sweden	102	22	81	11	49	162	89	30
Norway	108	30	86	15	52	172	11	22
Switzerland	530	160	188	65	227	564	315	246
United Kingdom	30	72	19	36	62	269	174	51
Turkey	414	50	-	-	-	-	-	-

NOTE 1: For Norway, damage costs data of the impacts on forests and on buildings were not available. We estimated the damage costs by adjusting the values for Sweden using the ratio as factor between the damage costs of the impacts on crops between Norway and Sweden. More precisely, the damage cost of the impacts on forests due to NOx emissions in Norway is calculated as follow:

DamageCost_forests_NOx_Norway =DamageCost_forests_NOx_NorwayDamageCost_crops_NOx_NorwayDamageCost_crops_NOx_Sweden

The same operation was conducted for the impacts on buildings due to NOx and SO2. For the impacts on forests due to NMVOC, we used the impacts on crops due to NMVOC as adjustment factor.

NOTE 2: For Switzerland, damage costs data of the impacts on forests and on buildings were not available. We estimated the Swiss damage costs by adjusting the values for Austria using the same procedure as for Norway.

Table 5 - Damage costs of heavy metals: all impacts, EU average, in €2019 per kg of atmospheric emissions

Pollutant	Damage cost
Lead	32'531
Cadmium	185'175
Mercury	16'903
Arsenic	11'044
Nickel	24
Chrome	3'129

tCO_2e), central (104 €2019/tCO_2e), and high (524 €2019/tCO_2e).[2, 3]

When necessary, the greenhouse gases other than CO2 are converted to a CO_2-equivalent (CO_2e) according to their Global Warming Potentials (GWPs) following the values recommended by the IPCC 6th Assessment Report.[4]

GRDP CALCULATION

The GrDP is calculated by subtracting the external costs associated with producing goods and services from the standard measurement of GDP:

$$GrDP_t = GDP_t - \sum_i p_i q_{it}$$

where p_i and q_{it} are the damage costs and quantity of pollutant i in the year t.

The data related to real GDP (i.e., adjusted for inflation, reference year 2019) is obtained from annual National Accounts (EUROSTAT NAMA database for European countries, Federal Statistical Office and State Secretariat for Economic Affairs (SECO) for Switzerland). For international comparison, we also compute the GrDP per capita, using population data from the EUROSTAT DEMO database.

LIMITATIONS AND FUTURE IMPROVEMENT

Although the current version of GrDP only considers the emissions to air of GHGs, air pollutants, and heavy metals, it covers most of the reported emissions to nature, as illustrated in **Figure 1** for Switzerland.

Still, some pollutants might have large impacts even at low quantities released. Moreover, many types of pollution are not yet precisely measured, e.g., plastic and microplastic pollution. The scope of the external costs calculated is also limited to the impacts that are known and valued. For example, in the case of biodiversity, only eutrophication issues in protected areas are considered in the present study. Finally, since we focused on environmental pollution and its impacts, the GrDP tells nothing about the exhaustion of resources such as

2 European Commission (EC), Directorate-General for Mobility and Transport, Essen, H., Fiorello, D., El Beyrouty, K., et al. (2020) Handbook on the external costs of transport: version 2019 – 1.1. Publications Office. https://data.europa.eu/doi/10.2832/51388

3 For studies focused on Switzerland, the prices are converted into CHF at the rate 1 CHF2019 = 0.8991 EUR2019, except for the central scenario, where we directly use the value of the Swiss carbon tax, i.e., CHF 120 as of 2022.

4 H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.). (2022). IPCC, 2022: Summary for Policymakers In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University

minerals and materials. Thus, the scope of the GrDP should be extended in future versions to better inform about the evolution of the environmental, social, and human capital.

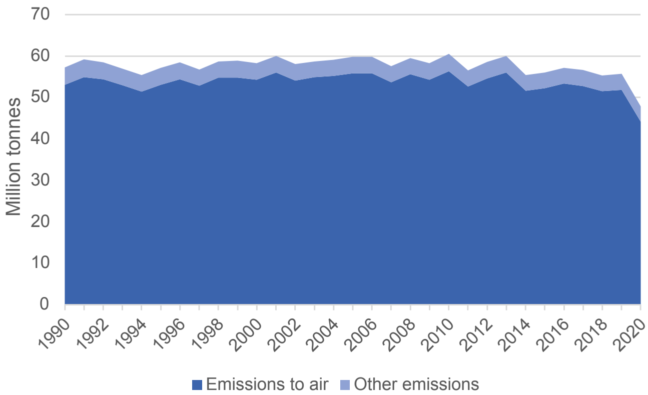

Figure 1 - Evolution of emissions to nature in Switzerland from domestic processed output (Source: [FSO – Environmental Accounting](#))