Material and energy productivity

Supplementary information

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This supplementary information contains the following:

1. A partial list of the resource productivity literature
2. A description of the international values and variability of the indicators
3. The full results of the consumption-income and productivity-income regressions for both Market Exchange Rate (MER) and Purchasing Power Parity (PPP) GDP, both in 2000 constant US dollars, along with a discussion of the changes in the income elasticities.
4. A list of acronyms.

It is 9 pages long and includes 3 tables and 1 figure.

1. Partial literature list

Resource productivity has been investigated in time series for single geographic entities, and its values are compared between countries in international studies (*1-15*). The time series studies usually compare changes in resource productivity compared to economic growth, since absolute dematerialization can only occur if productivity growth outpaces economic growth. In terms of the oft-debated Environmental Kuznets Curve (EKC) hypothesis, according to which environmental impacts first grow then decline with income growth, there should be an income level above which resource productivity grows faster than economic growth, a rare occurrence (*16-20*), although Roberts and Grimes showed that international carbon intensity may be following a Kuznets Curve (*3*). The EKC fails for material use in most industrialized countries (*21,22*). As Fischer-Kowalski and Amann point out, simultaneous increases in resource consumption *and* productivity are business-as-usual for most industrialized societies (*23*), which can be interpreted as a macro-economic manifestation of the rebound effect (*24,25*).

Recently, resource productivity was argued to be correlated with economic competitiveness in the EU (*26*), although this effect was shown to disappear when income levels are taken into account (*27*).

2. Values and variabilities of consumption and productivity

We summarize the magnitude, composition and variation in international resource consumption and productivity (Table S1). These quantities have been the subject of debate in the literature. For instance, Ang (*28*) posits that the range in variation of international energy intensity makes it a better indicator than the carbon contents of energy, while Goldemberg (*2*) argued that productivity is a more robust measure of national performance than either consumption or income, since it exhibits less international variation. As can be seen in Table S1, TPES per capita consumption is dominated by fossil fuels, whereas they are on average only a bit above half of the total DEC. The differences between TPES and DEC are due to the greater quantity of biomass accounted for in DEC, with remaining deviations in the fossil fuel and "other" categories caused by small differences in the factors used to convert mass into energy flows and the international sample size (in general, we use the largest sample size possible for each quantity). The largest average contributor to DMC is biomass, with fossil fuels only representing a bit more than a fifth of the total.

The variation in consumption is largest for the "other" energy categories (mainly hydraulic and nuclear electricity) and ores/industrial minerals on the material side. These categories are always a small share of the total resource consumption. Biomass consumption has the smallest international variability, even in TPES, where it is only incompletely accounted for. Fossil fuel consumption always has an international larger variation than biomass, unsurprisingly on par with carbon emissions and income.

These trends are reversed in the productivity measures. The variability of the productivity of fossil fuels is systematically smaller than that for biomass, indicating that fossil fuels are more closely tied to the economic scale than other resource types. (The extremely large value of the average TPES biomass productivity is mainly due to a few countries with very low biomass resources for energy use, like Saudi Arabia, Syria and others in the Middle East.) The "other" energy categories, and ores/industrial minerals, have by far the largest productivity variability, which can be understood by their small share in total resource use and large variability in consumption.

Table S1. International mean and coefficient of variation (*) of resource consumption and productivity. The country sample size ranges from 115 to 171.

	Consumption		**Productivity**		**Number of Countries**
	Mean	Coeff. of variation *	Mean	Coeff. of variation*	
	GJ/cap, t/cap, USD/cap		*USD/GJ, USD/t*		
Total Primary Energy Supply - TPES					
Total	99.6	1.25	56.7	0.81	131
Fossil	81.2	1.43	96.1	0.79	131
Biomass **	7.41	1.07	29821.6	5.23	125
Other ***	13.0	2.82	4489.0	4.02	115
Domestic Energy Consumption – DEC					
Total	133.2	1.12	34.6	1.16	164
Fossil	76.3	1.65	103.3	0.85	164
Biomass	45.7	0.90	166.9	1.82	167
Other ***	13.2	3.66	4977.6	3.91	140
Domestic Material Consumption – DMC					
Total	9.92	0.79	471.4	1.35	155
Fossil	2.03	1.47	4319.6	0.86	161
Biomass	3.62	0.84	2078.4	1.85	165
Const. Min.	2.83	1.00	1603.6	1.17	159
Ores/Ind. Min.	1.60	2.21	8968.9	1.04	131
GHG emissions					
Fossil CO_2	1.28	1.50	5840.5	0.85	162
Income					
MER $/cap	5'701	1.55			171
PPP $/cap	8'219	1.10			154

* The coefficient of variation is the sample standard deviation divided by the mean.

** The TPES biomass category is known as "combustible renewables and waste," and is a mixture of traditional biomass for heating and high-tech energy recovery from waste incineration.

*** The "Other" energy category includes all non-fossil non-biomass energy sources: principally hydraulic and nuclear electricity.

3. Full results for PPP and MER GDP

Table S2 and S3 present the full results of the regressions shown in Table 1 for both MER and PPP.

Table S2: Results of the regressions corresponding to eqs. 2 and 4 using MER GDP. R^2 is the goodness-of-fit; *a, b* and *c,d* are the coefficients. The figures in parentheses are the standard errors.

	(1) Consumption-Income Units: GJ/cap or t/cap, $/cap					(2) Productivity-Income Units: $/GJ or $/ton, $/cap					Number of countries
	R^2	*a*		Income elasticity *b*		R^2	*c*		*d*		
Total Primary Energy Supply											
Total	**0.736**	-0.471	(0.243)	0.582	(0.031)	**0.590**	0.471	(0.243)	0.418	(0.031)	131
Fossil	**0.691**	-2.756	(0.377)	0.810	(0.048)	0.110	2.756	(0.377)	0.190	(0.048)	131
Biomass	0.000	1.174	(0.902)	-0.009	(0.114)	0.387	-1.174	(0.902)	1.009	(0.114)	125
Other **	**0.466**	-6.151	(0.715)	0.910	(0.092)	0.008	6.151	(0.715)	0.090	(0.092)	115
Domestic Energy Consumption											
Total	**0.663**	1.220	(0.187)	0.435	(0.024)	**0.768**	-1.220	(0.187)	0.565	(0.024)	164
Fossil	**0.731**	-3.662	(0.336)	0.918	(0.044)	0.021	3.662	(0.336)	0.082	(0.044)	164
Biomass	0.047	2.983	(0.221)	0.082	(0.029)	**0.860**	-2.983	(0.221)	0.918	(0.029)	167
Other **	**0.491**	-6.469	(0.622)	0.943	(0.082)	0.003	6.469	(0.622)	0.057	(0.082)	140
Domestic Material Consumption											
Total	**0.636**	-0.733	(0.172)	0.366	(0.022)	**0.840**	0.733	(0.172)	0.634	(0.022)	155
Fossil	**0.690**	-7.385	(0.378)	0.924	(0.049)	0.015	7.385	(0.378)	0.076	(0.049)	161
Biomass	0.075	0.289	(0.220)	0.104	(0.029)	**0.857**	-0.289	(0.220)	0.896	(0.029)	165
Const. Min.	**0.755**	-3.070	(0.172)	0.491	(0.022)	**0.767**	3.070	(0.172)	0.509	(0.022)	159
Ores/Ind. Min.	**0.417**	-6.113	(0.566)	0.696	(0.073)	0.120	6.113	(0.566)	0.304	(0.073)	131
GHG emissions											
Fossil CO2	**0.729**	-7.502	(0.331)	0.891	(0.043)	0.039	7.502	(0.331)	0.109	(0.043)	162

Table S3: Results of the regressions corresponding to eqs. 2 and 4 using PPP GDP. R^2 is the goodness-of-fit; *a, b* and *c,d* are the coefficients. The figures in parentheses are the standard errors. R^2 values above 0.4 are shown in bold.

	(1) Consumption-Income Units: GJ/cap or t/cap, $/cap					(2) Productivity-Income Units: $/GJ or $/ton, $/cap					Number of countries
	R^2	*a*		Income elasticity *b*		R^2	*c*		*d*		
Total Primary Energy Supply											
Total	**0.750**	-2.922	(0.368)	0.806	(0.042)	0.149	2.922	(0.368)	0.194	(0.042)	122
Fossil	**0.735**	-6.483	(0.551)	1.157	(0.063)	0.048	6.483	(0.551)	-0.157	(0.063)	122
Biomass	0.000	0.921	(1.430)	0.029	(0.165)	0.233	-0.921	(1.430)	0.971	(0.165)	116
Other **	**0.506**	-10.208	(1.070)	1.295	(0.124)	0.050	10.208	(1.070)	-0.295	(0.124)	109
Domestic Energy Consumption											
Total	**0.688**	-0.719	(0.292)	0.619	(0.034)	**0.456**	0.719	(0.292)	0.381	(0.034)	149
Fossil	**0.760**	-7.779	(0.514)	1.303	(0.060)	0.146	7.779	(0.514)	-0.303	(0.060)	149
Biomass	0.080	2.381	(0.352)	0.150	(0.041)	**0.737**	-2.381	(0.352)	0.850	(0.041)	152
Other **	**0.551**	-11.211	(0.962)	1.410	(0.113)	0.094	11.211	(0.962)	-0.410	(0.113)	128
Domestic Material Consumption											
Total	**0.682**	-2.408	(0.258)	0.525	(0.030)	**0.636**	2.408	(0.258)	0.475	(0.030)	143
Fossil	**0.747**	-11.827	(0.553)	1.346	(0.065)	0.163	11.827	(0.553)	-0.346	(0.065)	147
Biomass	0.129	-0.468	(0.339)	0.188	(0.040)	**0.734**	0.468	(0.339)	0.812	(0.040)	151
Const. Min.	**0.762**	-5.170	(0.272)	0.686	(0.032)	**0.403**	5.170	(0.272)	0.314	(0.032)	146
Ores/Ind. Min.	**0.441**	-9.413	(0.871)	1.005	(0.101)	0.000	9.413	(0.871)	-0.005	(0.101)	127
GHG emissions											
Fossil CO2	**0.767**	-11.552	(0.493)	1.271	(0.058)	0.130	11.552	(0.493)	-0.271	(0.058)	148

PPP and MER incomes are obviously closely correlated. When we fit them to the equation

(Eq. S1) $$Income_{PPP} = \exp(f) \cdot Income_{MER}{}^{g}$$
$$\Leftrightarrow \log(Income_{PPP}) = f + g \cdot \log(Income_{MER})$$

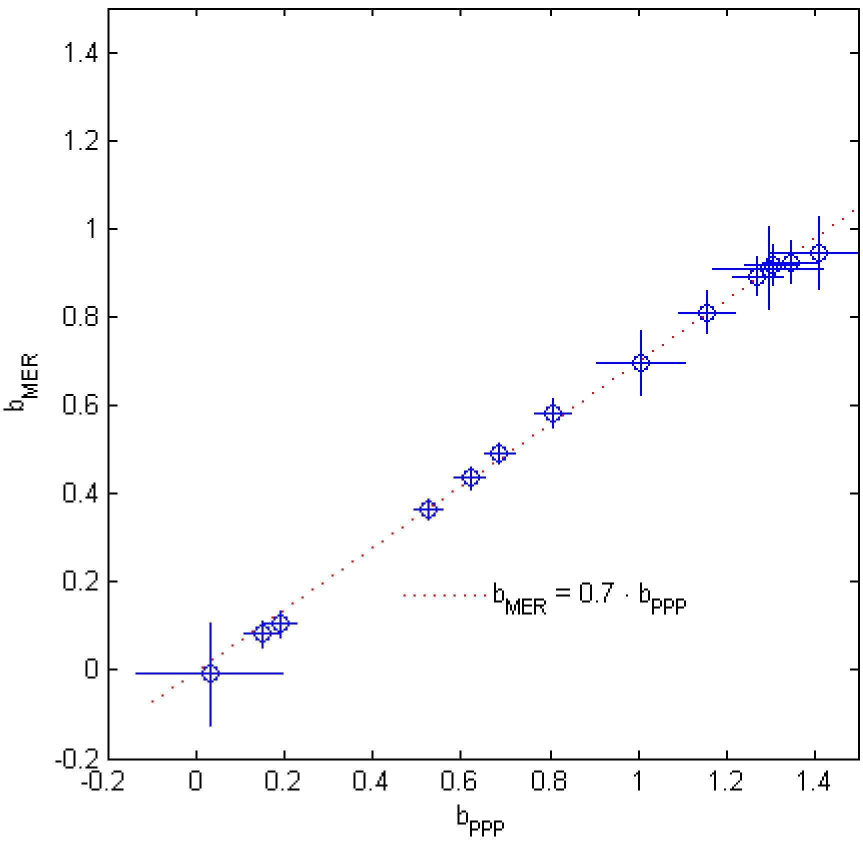
for the coefficients *f* and *g*, the goodness-of-fit R^2 is 0.95, which implies that 95% of the variation in PPP income can be explained by MER income. The coefficients *f* and *g* are 3.19 +/- 0.10 and 0.70 +/- 0.01 respectively.

The exponent *g* is especially interesting, since it should relate income elasticity measured with MER and PPP incomes:

(Eq. S2) $$b_{MER} = g \cdot b_{PPP}$$

When we compare the elasticities measured with PPP and MER incomes, we find that this is indeed the case (figure S1).

Figure S1: elasticities obtained with MER incomes (vertical axis, table S2) and PPP incomes (horizontal axis, table S3). The line is given by eq. S2 with g = 0.7, not by a regression.



There is thus a simple systematic relation between PPP and MER, and it does not matter much which is used for analysis, as long as the choice is made explicit. Whether or not this relationship changes over time (all data used in this study was from the year 2000) is not clear.

Elasticities are systematically higher if measured in PPP currencies and lower in MER: this means that a simple interpretation of elastic-proportional-inelastic resource may change based upon the currency used, since fossil fuels are elastic in PPP terms, but inelastic (almost proportional) in MER terms. Again, the implications are not particularly dramatic in terms of the analysis, as long as currency unit choice is made explicit and is consistent throughout.

4. Acronyms

DEC = Domestic Energy Consumption
DMC = Domestic Material Consumption
DMI = Domestic Material Input
IEA = International Energy Agency
GHG = Greenhouse Gas
GDP = Gross Domestic Product
MER = Market Exchange Rate

PPP = Purchasing Power Parity
USD = United States Dollar
TPES = Total Primary Energy Supply

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