Climate Change Economics Lab

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Material Demand and Material Efficiency: A Stochastic Frontier Analysis

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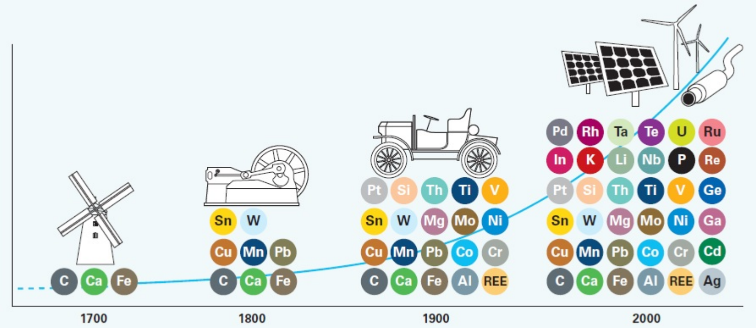
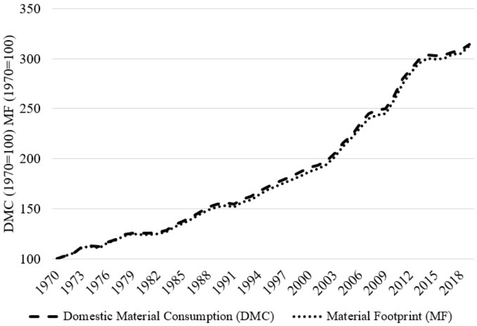
Materials



Source: Zepf et al. (2014)

- Energy production industry builds on mills and steam engines in the 17 and 18 centuries, which need only a few materials, such as iron, carbon, copper, or manganese.

Material Consumption from 1970 to 2019

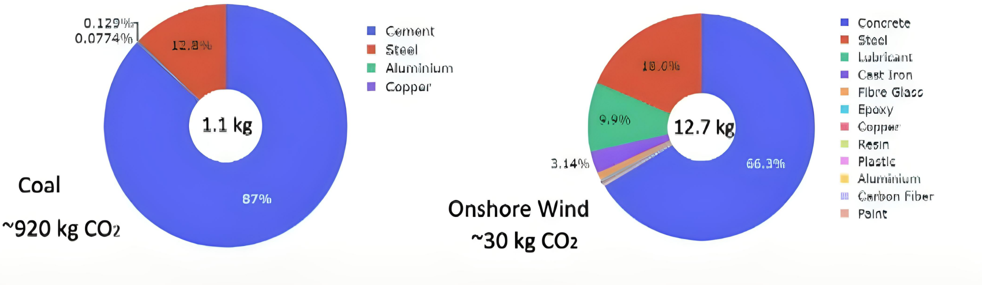


Source: Global Material Flows Database (2022)

- The OECD projects that global material use will be doubled in 2060, compared to 2011.
- Non-metallic minerals and metals will represent more than 60% of this growing demand.

Why are materials important?

- To deliver 1 MWh of electricity, we need the following materials for power plants



Source: Barron et al. (2022)

- If the 20th century energy goal was about access to the oil and gas, the 21st century will be about the access to materials.

Growing Demand for Materials

Actual (2021) and Projected (2050) Demand under IRENA's 1.5°C Scenario

Material	Demand in 2021 (Mt/year)	Demand in 2050 (Mt/year)	Source
Cu Copper	30 Mt/yr	50-70 Mt/yr	Elshkaki *et al.* (2016); ICGS (2021); INSG (2021)
Ni Nickel	2.77 Mt/yr	5-8 Mt/yr	Elshkaki *et al.* (2017)
Li Lithium	0.3 Mt/yr	2-4 Mt/yr	Moore and Bullard (2021)
Nd Neodymium	0.03 Mt/yr	0.2-0.5 Mt/yr	Barrera (2021); Joint Research Centre (2020, 2021); Deetman *et al.* (2021)

Source: International Renewable Energy Agency (2022)

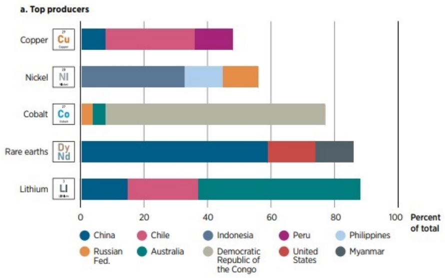
Economically vital

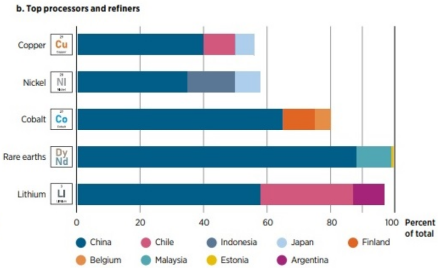
Source: Canada Mining

- Tungsten for smartphones, gallium for many light-emitting diodes (LEDs), copper for electronics, and silicon metal for semiconductors.
- For example, 50 different metals in different quantities are needed to produce a standard smartphone (EC, 2018).

Supply Risk

- Raw materials supply may not be able to respond quickly to this increasing demand, slowing the clean energy transition.

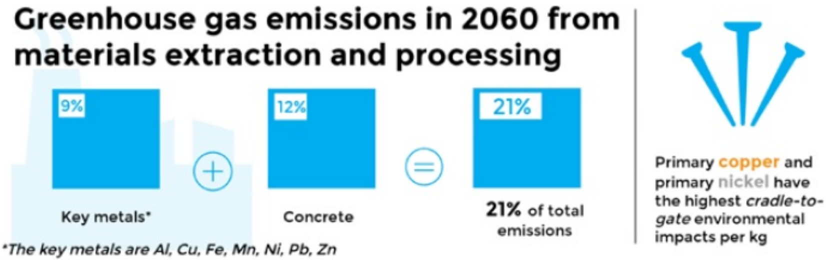




Source: IRENA (2022)

Environmental Risk

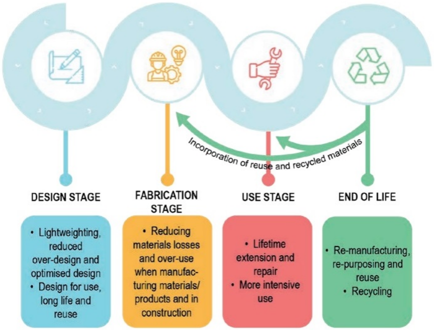
- Growing demand for materials does not come for free but at environmental cost.



Source: OECD (2019)

Material Efficiency

- IEA (2021) defines material efficiency as the strategies that reduce material demand or switch to lower-emission materials or production routes.



Source: IEA (2019)

- Efforts to reduce emissions largely center around energy systems (UNEP, 2022).
- The energy efficiency performance of countries is well below the level needed to achieve global climate and sustainability goals, and suggests that global developments in energy efficiency have been declining since 2015 (IEA, 2020).
- Only energy efficiency is not sufficient, we need more than energy efficiency!

What to do!

- The main purpose of this paper is to explore the main determinants of the material demand and evaluate material efficiency performance of the EU countries.
- Unlike the growing literature on energy efficiency, there is no study in the literature than quantify material demand and efficiency.
- We also decompose material efficiency into two parts:
  - persistent or long-term time-invariant efficiency
  - transient or short-term time-varying efficiency

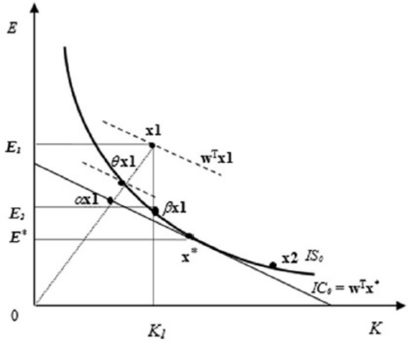
*While the persistent inefficiency might arise from some structural problems in the production process, such as infrastructural weaknesses, the transient inefficiency might be related to some non-systematic reasons that can be resolved in the short term.
*Short-term problems: inefficient supplier selection, sub-optimal resource allocation, delaying the substitution of old and inefficient equipment.
*While policies focusing on long-term structural changes should be implemented in cases where persistent inefficiency scores are higher, short-term policies should be designed in cases where transient inefficiency scores are higher.

How to do!

- Material intensity is still one of the most frequently used indicators.
  - defined as the ratio of material consumption to gross domestic product
  - only considers inputs itself
  - ignores other factors affecting material efficiency, such as structure of economy, input prices and so on.
- To address this deficiency, what we are looking for is to calculate a material efficiency based on the main determinants of material demand
- A frontier approach: Stochastic Frontier Analysis
  - separate time-varying transient efficiency from both time-invariant persistent efficiency and unobservable time-invariant country-specific effects
  - highly important from the climate policy perspective

Stochastic Frontier Analysis

- The basic theoretical idea behind the SFA is that there is an ideal frontier that no country can exceed. Therefore, deviations from this ideal case measure the countries' individual input inefficiency.



Source: Filippini and Hunt (2015)

SFA Models-Standard Panel Data

- The earliest SFA panel data models mainly focus on controlling country effects.

$$y_{it} = \beta_0 + f(x_{it}; \beta) + \epsilon_{it}$$

$$\epsilon_{it} = v_{it} - u_i$$

- To capture time-invariant persistent efficiency, they make country effects (fixed or random) one-sided and interpret them as efficiency.
- There are also some other time-varying FE and RE inefficiency models.
  - In the FE models, the time-varying inefficiency term is non-stochastic (i.e. function of time).
  - Inefficiency effect is composed of either a random term or a combination of a time-invariant stochastic term and a time-varying deterministic function in the RE model.

SFA Models-TFE and TRE

- One of most frequently employed SFA model
- There are two important innovations here
  - country effects are separated from efficiency
  - time-varying efficiency

$$y_{it} = \beta_i + f(x_{it}; \beta) + \epsilon_{it}$$

$$\epsilon_{it} = v_{it} - u_{it}$$

- If one treats β_i as fixed parameters that are not part of inefficiency, then the model becomes the "true fixed-effects" panel stochastic frontier model.
- The model is labeled as a "true random-effects" stochastic frontier model when β_i is treated as a random variable.

SFA Models-Three Components

- Capturing both time-invariant persistent and time-varying transient efficiency simultaneously.
- Persistent efficiency is measured by country effects, meaning that it fails to separate the persistent part from the country effects.

$$y_{it} = \beta_0 + f(x_{it}; \beta) + \epsilon_{it}$$

$$\epsilon_{it} = v_{it} - u_{it}$$

$$u_{it} = u_i + \tau_{it}$$

- u_{it} is composed of two parts
  - u_i is time-invariant persistent part
  - τ_{it} is time-varying transient part

SFA Models-Four Components

- Capturing country effects, persistent efficiency, and transient efficiency simulatenously.

$$y_{it} = \beta_0 + f(x_{it}; \beta) + \mu_i + v_{it} - \eta_i - u_{it}$$

- where μ_i is unobserved country effect, v_{it} is random shocks; η_i is long-run (time-invariant) persistent inefficiency, and u_{it} is short-term (time-varying) transient inefficiency.
- These components appeared in other models in various combinations but not all at the same time in one model. This is the novelty of this model.

Estimation

- We follow a multi-step procedure
  - We first estimate the following transformed four-component model with the RE and obtain β parameters and predicted values of α_i and ε_{it}.

    $$y_{it} = \beta_0^* + f(x_{it}; \beta) + \alpha_i + \varepsilon_{it}$$

    where $\beta_0^* = \beta_0 - E(\eta_i) - E(u_{it})$, $\alpha_i = \mu_i - \eta_i + E(\eta_i)$, and $\varepsilon_{it} = v_{it} - u_{it} + E(u_{it})$. While v_{it} and μ_i are assumed to be normally distributed, η_i and u_{it} are often assumed to follow a half-normal distribution. α_i and ε_{it} have zero mean and constant variance.
  - In the second step, the predicted values of α_i are used as the dependent variable to estimate persistent inefficiency η_i with SF model.

    $$\alpha_i = \mu_i - \eta_i + E(\eta_i)$$

  - In the third step, we estimate the time-varying transient inefficiency u_{it} with the predicted values of ε_{it}.

    $$\varepsilon_{it} = v_{it} - u_{it} + E(u_{it})$$

From Estimation to Efficiency Scores

- Country-specific transient and persistent efficiency performance of countries is calculated using the conditional mean estimator of u_{it} and η_i (Jondrow et al. 1982).
- Overall efficiency is obtained as a product of the transient and persistent efficiency scores.

$$PE = \exp(-\eta_i)$$

$$TE = \exp(-u_{it})$$

$$OE = PE \times TE$$

- All these values take value between 0 and 1.
- It is relative score based on the country sample.
- 1 indicates a fully material-efficient country.
- Application: Stata (Kumbhakar et al. 2015 and Belotti et al. 2012).

Dataset

Description	Abbr.	Source
Domestic material consumption (t)	DMC	IRP Global Material Flow Database
Gross domestic product (constant 2015$)	GDP	World Bank Development Indicators
Population (total)	POP	World Bank Development Indicators
Land area (km^2)	AREA	World Bank Development Indicators
Industry, value added (% of GDP)	ISH	World Bank Development Indicators
Services, value added (% of GDP)	SSH	World Bank Development Indicators
Real material price (2010=100)	MP	World Bank Commodity Price Data
Energy consumption (TWh)	EC	BP Statistical Review of World Energy
Trade openness (% of GDP)	TO	World Bank Development Indicators

*Weighted global material price data based on 7 different global metal and mineral prices is deflated by using each country CPI data.

Model Specification

- Following the input demand function* structure of Filippini and Hunt (2011) and many others in the existing literature, we estimate the following model**

$$lnDMC_{it} = \beta_0 + \beta_1 lnGDP_{it} + \beta_2 lnPOP_{it} + \beta_3 lnAREA_t + \beta_4 lnISH_{it} + \beta_5 lnSSH_{it} +$$

$$\beta_6 lnMP_{it} + \beta_7 lnEC_{it} + \beta_8 lnTO_{it} + \beta_9 t + \beta_{10} t^2 + \mu_i + v_{it} - \eta_i - u_{it}$$

*Input demand function: the frontier shows the minimum level of input by a country for a given output and estimates the input inefficiency by controlling other factors, such as output, price.
**We assume a widely-used Cobb-Douglas production function and specify our model in a log-log form.

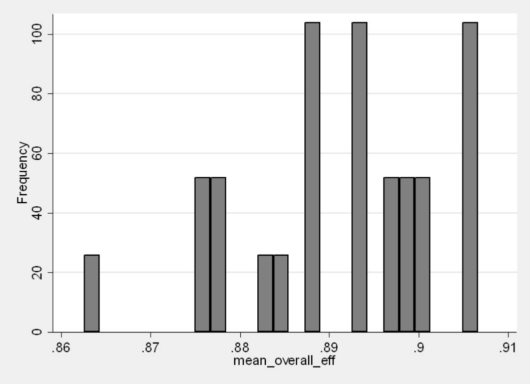
Determinants of Material Demand

Variables	lnDMC
lnGDP	0.906***
lnPOP	-0.668***
lnAREA	0.116
lnEC	0.268***
lnMP	0.000364
lnISH	0.0621
lnSSH	-0.787***
lnTO	-0.508***
t	0.0197***
tsq	-0.000904***
Constant	9.897***
Observations	650
Number of obs.	26
R	0.7980

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

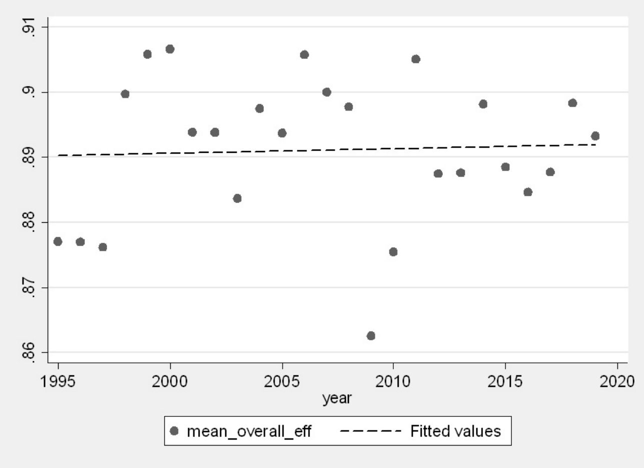
- Income is found to be positive and statistically significant impact on material consumption.
- Population has a significant negative effect on material consumption.
- The effect of area and material price is not statistically significant.
- While the share of industry is estimated to be positive, the share of service has negative effect on DMC.
- There is a positive relationship between EC and DMC.
- Both trend variables are statistically significant.

Material Efficiency-Overall I



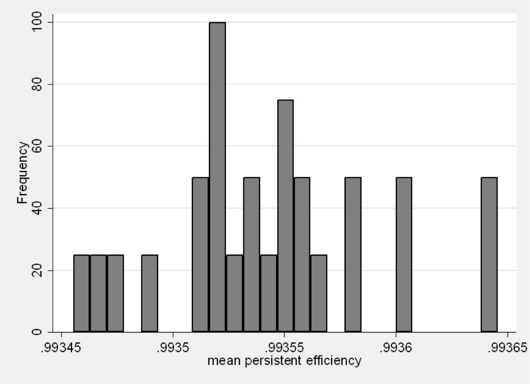
- Overall average efficiency scores ranges between 0.86 and 0.91 for the sample group over the period 1995-2019.
- These ME scores range within a relatively narrow band and are significantly higher, suggesting that the EU countries are considerably material efficient.
- The EU's ambitious goals and harmonised stringent regulations on climate change could explain both high ME efficiency scores as well as narrow band for these scores.

Material Efficiency-Overall II



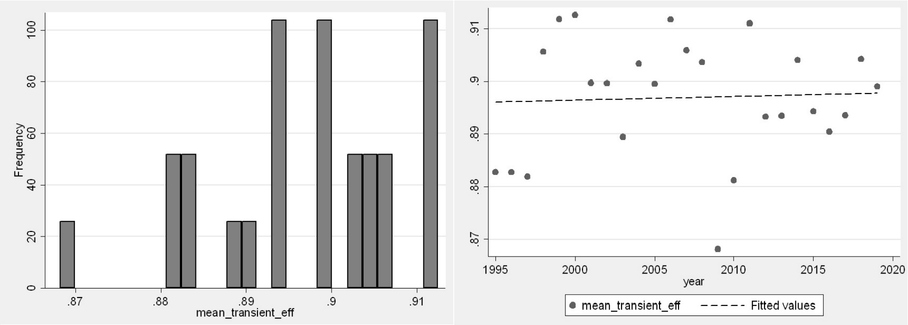
- Overall efficiency performance of the EU countries has an increasing trend.

Material Efficiency-Persistent



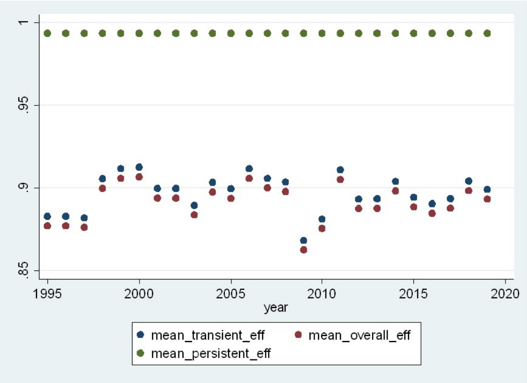
- It is found that persistent material efficiency is very high and takes values varying in a narrow range.
- The EU as a whole does not have some structural problems that we urgently need to design and implement with some long-term policies.
- Much of the variation in overall efficiency is explained by the transient part.
- It is more likely that persistent efficiency will always be higher than transient part for all countries in the EU.

Material Efficiency-Transient



- The values of transient part are changing within a wider range.
- This means that much of the variation in overall efficiency comes from this part.
- Overall material efficiency performance of the EU countries are more determined by the transient part.
- So for the policy making, we should pay more attention to this part.

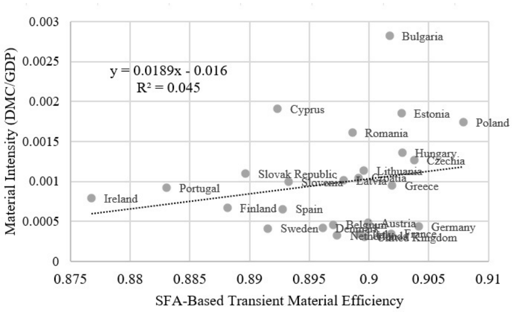
Persistent vs. Transient Material Efficiency



Variable	Obs	Mean	Std. dev.	Min	Max
overall_eff	650	.891094	.0493526	.6550493	.9661068
transie~_eff	650	.8968849	.0496716	.6593137	.9723963
persist~_eff	650	.9935432	.0000467	.9934554	.9936455

- Overall and transient material efficiency performances move together.
- Yet, persistent part significant differ from these two scores.

Transient Material Efficiency vs. Material Intensity



- There is a positive relationship between material intensity and material efficiency.
- Material intensity may not be the good measure of material efficiency.

Conclusion

- There is a growing demand for materials.
- The improvement of material efficiency is one the best available and easily-feasible tools that can support our climate targets.
- We should corrrectly measure it.
- There is a room that we can move forward.
- Material efficiency seems to have a greater potential for further reductions in emissions once policies are directly targeted for efficient use of material, which can enable the EU to achieve to become carbon-neutral by 2050.
- One more thing to add: rebound effect

Спасибо!

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