Energy Efficiency Measurement:
From Single to Composite Indicators

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Introduction

- Two big challenges in the 21st century: Climate Change & Energy security

- Improving energy efficiency helps to
  - Reduce energy consumption and CO2 emissions
  - Enhance energy security
  - Decrease energy cost
  - Increase business competitiveness
  - Create a positive image
Introduction

Energy efficiency is a generic term which means different things for different people/organizations.

Which model more energy efficient?

Source: http://www.fueleconomy.gov/feg/byclass.htm

China’s Industrial energy efficiency targets by 2020
Introduction

- The indicator approach prevails in energy efficiency analysis
- Different types of indicators have been used in various application contexts
- The selection/development of an appropriate energy efficiency indicator is dependent on its definition

**Question:** how to define and measure energy efficiency at economy level?
Energy efficiency concepts

- In physics and engineering, the energy efficiency of a process, denoted by \( \eta \), is defined as:

\[
\text{efficiency } \eta = \frac{\text{output}}{\text{input}}
\]

where \textit{output} is the amount of mechanical work (in watts) or energy released by the process (in joules), and \textit{input} is the quantity of work or energy used as input to run the process.

In physics and engineering, it is a \textit{dimensionless} number with a value between 0 and 1. Due to the principle of conservation of energy, energy efficiency within a closed system can never exceed 100%.
Energy efficiency concepts

- Descriptions/concepts of energy efficiency at macro level
  - “How effectively energy is being used for a given purpose”  (OEE, Canada)
  - “A change to energy use that results in an increase in net benefits per unit of energy”  (EECA, NZ)
  - “The ratio of the amount of energy services provided to the amount of energy consumed”  (EIA, USA)
  - “The activity or product that can be produced with a given amount of energy”  (EERA, USA)
  - “Energy efficiency is the first fuel of a sustainable global energy system”  (IEA)
  - "A ratio between an output of performance, service, goods or energy, and an input of energy"  (European Commission, Directive 2006/32/EC)
  - “A reduction in the energy used for a given service (heating, lighting, etc.) or level of activity”  (World Energy Council)
Energy efficiency concepts

- It is often defined as the inverse of *energy intensity*.
- At the device/process level, there is little difference between *energy efficiency* and *energy intensity* - one is simply the inverse of the other.
- At the macro level, energy efficiency is not a meaningful concept because of *the heterogeneous nature of energy services*.
- An intensity measure can be calculated at the macro level, although its information content is limited without knowing the underlying sector details.
- At economy level, the *substitution effect* between energy and other inputs make the measurement of energy efficiency be more complicated.
Energy efficiency concepts

Examples of *energy intensity indicators* at various levels of aggregation of energy consumption:

<table>
<thead>
<tr>
<th>Country</th>
<th>Economy-wide</th>
<th>E/GDP</th>
<th>E/capita</th>
<th>E($)/GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>E/passenger-km</td>
<td>E/tonne-km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td>E/value-added</td>
<td>E($)/value-added</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>E/household</td>
<td>E/(floor space)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial/Institutional</td>
<td>E/(floor space)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-sector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger transport</td>
<td>E/passenger-km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-metallic mineral products</td>
<td>E/value-added</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Educational buildings</td>
<td>E/(floor space)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End-use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>E/km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>E/tonne</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting</td>
<td>E/(floor space)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The energy-GDP ratio, i.e. energy use per unit of GDP, has long been used by researchers and analysts to track changes in economy-wide energy efficiency. However, the changes in the energy-GDP ratio may arise from sources unrelated to energy efficiency, such as activity structure change.

Composite energy intensity indexes (CEIs) may be used in place of, or to complement, the energy-GDP ratio for tracking energy efficiency trends.

How to construct a composite energy intensity (CEI)?
1. Bottom-up approach (e.g. ODEX)
2. Decomposition cum aggregation (DCA) approach
The DCA approach

**Step 1.** Use index decomposition analysis to isolate the energy intensity effects at lower levels (e.g. sub-sector level)

**Step 2.** Construct CEI use the energy intensity effects obtained.

How to select an index decomposition analysis method?

**Answer:** LMDI

\[
E_i = \sum_{j=1}^{n_i} E_{ij} = \sum_{j=1}^{n_i} Q_i \frac{Q_{ij}}{Q_i} \frac{E_{ij}}{Q_{ij}} = \sum_{j=1}^{n_i} Q_i S_{ij} I_{ij}
\]

\[
\Delta E_{i}^{0,T} = E_{i}^{T} - E_{i}^{0} = \Delta E_{i-act}^{0,T} + \Delta E_{i-str}^{0,T} + \Delta E_{i-int}^{0,T}
\]
Alternative DCA models

- **LMDI methods**: LMDI-I, LMDI-II
- **Decomposition form**: Additive, Multiplicative
- **Indicator for decomposition**: Energy consumption level, Aggregate energy intensity
- A total of eight DCA models:

\[
CEI_{i}^{\Delta E} = \frac{E_{i}^{T}}{EH_{i}^{T}} \times \frac{Q_{i}^{T}}{Q_{i}^{T}} = \frac{E_{i}^{T}}{E_{i}^{T} - \Delta E_{i-int}^{0,T}} \\
CEI_{i}^{\Delta I} = \frac{I_{i}^{T}}{IH_{i}^{T}} = \frac{I_{i}^{T}}{I_{i}^{T} - \Delta I_{i-int}^{0,T}} \\
CEI_{i}^{D} = D_{i-int}^{0,T} = \prod_{j=1}^{n_{i}} \left( \frac{I_{ij}^{T}}{I_{ij}^{0}} \right)^{w_{ij}} \\
CEI_{i}^{R} = R_{i-int}^{0,T} = \prod_{j=1}^{n_{i}} \left( \frac{I_{ij}^{T}}{I_{ij}^{0}} \right)^{w_{ij}}
\]
A simple example of DCA application

<table>
<thead>
<tr>
<th>Year 0</th>
<th>Year T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>$E_T$</td>
</tr>
<tr>
<td>Sector 1</td>
<td>60</td>
</tr>
<tr>
<td>Sector 2</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Energy consumption approach

<table>
<thead>
<tr>
<th>Additive</th>
<th>Multiplicative</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMDI-I</td>
<td>0.853</td>
</tr>
<tr>
<td>LMDI-II</td>
<td>0.850</td>
</tr>
</tbody>
</table>

Energy intensity approach

<table>
<thead>
<tr>
<th>Additive</th>
<th>Multiplicative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive</td>
<td>0.842</td>
</tr>
<tr>
<td>Multiplicative</td>
<td>0.839</td>
</tr>
</tbody>
</table>
Application of DCA to the Manufacturing Sector in China
An observation

- The CEI model by multiplicative LMDI approach

\[ CEI_i = D_{i-int}^{0,T} = \prod_{j=1}^{n_i} \left( \frac{I_{ij}^T}{I_{ij}^0} \right)^{w_{ij}} \]

- It is quite similar to the bottom-up approach and the tricky part lies in the determination of the weights
Another issue: How to consider the substation effect?

- CEI is still a partial indicator
- Energy needs to be accompanied with other inputs (e.g. labor) in order to generate outputs
- Total factor energy efficiency (TFEE) concept was proposed in 2006, which was followed by a number of relevant studies
The ways for deriving TFEE

- Frontier approaches are widely used
- There are two main frontier analysis techniques: Data envelopment analysis (DEA), Stochastic frontier analysis (SFA)
- In practice, SFA has been used for developing ENERGY STAR plant Energy Performance Indicators
DEA methodology

- Engineering-Science definition of efficiency — “Output-to-Input Ratio”, i.e.
  \[ \text{Eff} = \text{output}/\text{input} \ (0 \leq \text{Eff} \leq 1) \]
- In the case of multiple inputs and outputs, \( \text{Eff} = \frac{\text{weighted sum of outputs}}{\text{weighted sum of inputs}} \)

I. One input/one output case

II. Two inputs case
What is congestion?

Congestion lies in the non-economic area of production.

- Nobel Prize laureate D McFadden (1978) first introduced congestion into production area.
- When the marginal output of certain input becomes negative, the production technology is congested.
- In the isoquants, congestion occurs in the back-bending area where the increase of some particular input is at the cost of other input’s increase.
Congestion in production

- It might be difficult to observe a decline in output especially at macro level
  - The negative marginal output of one input is usually offset by the positive marginal output of other input, but it could occur because of the existence of limited factors.
  - The quality of these factors are usually not accounted for in economic analysis because they are difficult to control.

**Micro-level**

- Excessive energy input
- Boiler
- Output
- Incomplete combustion

**Macro-level**

- Excessive inputs
- Industry System
- Output

The quality of working environment, management activity and the natural resources might depredate with the increasing of inputs
TFEE with congestion: Graphical illustration
Concluding remarks

When you can measure what you are speaking about, and express it in numbers, you know something about it; when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.

Lord Kelvin
Concluding remarks

- Indicators are simple but particularly useful in quantifying energy efficiency progress.
- Energy intensity indicators prevail in many application contexts.
- At macro level, aggregate energy intensity (e.g. energy consumption per unit of GDP) is not a good proxy for tracking energy efficiency performance.
- Need to isolate out the non-efficiency effects and consider the substitution effect.
- Further work is required to consolidate different methods and produce a unified framework for measuring economy-wide energy efficiency performance.
Some relevant work

Finally, about Energy Policy

Editorial Policy has some changes since 2015


Impact factor: 4.880
5 Year impact factor: 5.458
Thank you!

Welcome to visit my group at China University of Petroleum, Qingdao.