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Analysing residential energy consumption using index decomposition analysis

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HIGHLIGHTS

- We reviewed 20 residential energy consumption studies using IDA.
- We classify them into two different types and describe the driving forces captured.
- We propose a hybrid model to tracking residential energy consumption trends.
- The hybrid model is applied to residential electricity consumption in Singapore.

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ABSTRACT

Index decomposition analysis (IDA) has been a popular tool for studying changes in energy consumption over time in major energy consuming sectors. In the basic form, it allows such changes to be decomposed to give contributions associated with three different effects, namely activity, structure and intensity effects. In the literature, IDA studies on the residential sector, unlike those on industry and transport, show large variations in the choice of the activity indicator that drive energy consumption. Such variations greatly affect the decomposition results obtained and what these results capture. We investigate these issues and classify the conventional practices into two different decomposition models. We then propose a hybrid model which can better decompose changes of residential energy consumption and apply it to the data of Singapore. The relationships between the hybrid and the conventional models are analysed.

1. Introduction

Index decomposition analysis (IDA) has been a popular tool for studying changes in energy consumption in major energy consuming sectors in the economy. In the most basic form, it is used to decompose changes in energy consumption in a sector into contributions from three different effects, namely changes in overall activity level, activity structure and energy intensity. They are commonly referred to as the activity, structure and intensity effects respectively. In such a basic form, the IDA identity is given by

$$E = \sum_i E_i = \sum_i A \frac{A_i}{A} \frac{E_i}{A_i} = \sum_i AS_i I_i \quad (1)$$

where E is the total energy consumption and A is the overall activity level of a sector. The total energy consumption and activity are disaggregated into subsectors (or sub-categories) and E_i and A_i are the corresponding values for sub-sector i. A change in the total energy E from one year to another is decomposed and quantified in terms of changes arising from A (activity effect), S given by A_i/A (structure effect) and I_i given by E_i/A_i (intensity effect). Through IDA studies, the mechanisms of change in energy consumption in a sector can be better understood. This has been found to be useful in energy policy analysis, i.e. for understanding the past, assessing the present situation and studying possible futures with regard to energy consumption and energy-related carbon emissions.

A literature survey of IDA studies can be found in [1], and a comparison and evaluation of IDA methods in [2]. Choosing an appropriate activity indicator, i.e. A and hence A_i, is crucial in empirical IDA studies. The indicator will be taken as the key driver of energy consumption and will dictate the ways structure change and energy intensity (and energy efficiency) as shown in Eq. (1) are defined. For some energy consuming sectors, such as transport and industry, the preferred activity indicators and the corresponding structure and intensity effects are well defined and widely accepted.[1] As to the residential sector, the issue is more complex as there are large variations in the choice among studies. The reason

[1] For instance, in the case of the transport sector, passenger-kilometres and tonne-kilometres are often taken as the activity indicators for analysing passenger and freight transportation energy consumption respectively. Structure change and energy intensity change are defined accordingly, i.e. in the case of passenger transport in terms of changes in model traffic mix measured by passenger-kilometres for structure change and in terms of changes in modal energy intensities given by energy consumption per passenger-kilometre.

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Table 1
Drivers of residential energy consumption as reported in the literature.

Classification	Key drivers/indicators
Demographics	Household number
	Population
Economic factors	Energy prices
	Household income
Individual factors	Awareness
	Consuming behaviour
Climate	Heating degree days (HDD)
	Cooling degree days (CDD)
Technology	Energy efficiency
Life-style	House size
	House occupancy
	Appliance ownership
Structure	Population segment by region, income group, age profile, etc.
	Housing type segment by number of rooms, number of residents, etc.

is that changes in the overall energy use in the sector can be due to a number of reasons and it is difficult to have a single activity indicator that is equally applicable for all energy end-uses. This has implications on how decomposition analysis is to be conducted, the decomposition results obtained, and extended applications such as tracking of energy efficiency trends and energy-related emissions. Indeed in using IDA to track economy-wide energy efficiency trends, one of the challenges is to analyse the performance in the residential sector.

In this study, we look into the issues of analysing changes in residential energy consumption using IDA. In Section 2, we identify possible underlying forces that drive residential energy consumption and whose impact could be estimated using IDA. A literature survey is then conducted and the past and current practices are described in Section 3. Our focus is on the formulation of the IDA identity including the choice of the activity indicator and the meanings of the various effects estimated. We further show that the conventional practices may be grouped under two different IDA models. We then propose a hybrid IDA model that can better capture the activity, structure, intensity effects, as well as other effects, in Section 4. We explain the relationships between the hybrid model and the conventional models. In Section 5, we apply the proposed hybrid model to the data of Singapore. Section 6 concludes.

2. Drivers of residential energy consumption

At the aggregate level, residential energy consumption is affected by socio-economic, climatic and cultural factors. Haas [3] presents a set of drivers of residential energy consumption and construct an indicator pyramid by end-use. In practice, not all of these indicators are required for assessing residential energy consumption and only some have been adopted in the literature. We are able to identify 12 of them that have been adopted in IDA studies and they are shown in Table 1. The 12 indicators are grouped into seven categories, each with fairly similar drivers of residential energy consumption. Most drivers under the five categories demographics, climate, technology, lifestyle and structure have been used by researchers. The impacts of these drivers can be quantified using IDA models. Those in the remaining two, i.e. economic factors and individual factors, are indirect drivers and have interactions with the drivers in other categories. Household income is the most important indirect driver. It has interactions with factors in the categories of 'Lifestyle' and 'Individual'. The impact of household income is studied in [4,5] and is indirectly estimated by tracking the contribution of population segments shifts in income groups in [6].

As to the factors related to culture and policy as mentioned in [3], the influence of the former has so far not been specifically considered in IDA studies. Different cultures and living habits will have an impact on energy requirements, and changes in the composition of the population are likely to have an influence on the overall residential energy consumption, as shown in [7]. Policies on residential energy consumption are studied in [5,6].

3. A literature survey

In the literature, 20 studies can be found using IDA analysing residential energy consumption or energy-related carbon emissions. Studies dealing with emissions are included in our study since they are direct extensions of energy studies. These 20 studies and their main features are summarised in Table 2. As shown in the first two columns, most of the studies were reported in or after 2000 and a reasonably wide range of countries or economies are covered. Column 3 shows the time periods in which changes in energy consumption or emissions are decomposed. Columns 4 to 6 show the activity indicator and the terms that define structure and energy intensity in the respective studies. Population and household number are the two most widely used activity indicators, and they respectively account for 13 and six of the 20 studies. The last column shows other specific factors considered in some studies. Examples of these factors are household income, weather and level of service.[2] From Table 2, it can be seen that large variations exist among studies in the choice of the activity indicator. As a result, there are variations among studies as to how structure change and energy efficiency are defined.

3.1. Households as the major consumption unit

When the number of households is chosen as the activity indicator, structure effect and intensity effect are respectively measured as the proportion of each type of households defined and energy consumption per household. From Eq. (1) and let N be the total number of households, the corresponding decomposition identity is given by:

$$E = \sum_i E_i = \sum_i N \frac{N_i}{N} \frac{E_i}{N_i} = \sum_i N S_i I_i \quad (2)$$

Instead of the number of households, the total floor space expressed in F can also be used as the activity indicator. In this case, we have:

$$E = \sum_i E_i = \sum_i F \frac{F_i}{F} \frac{E_i}{F_i} = \sum_i F S_i I_i \quad (3)$$

In the above, N_i, F_i and E_i are respectively the number of households, gross floor area, and energy consumption for housing (or household) type i. It is clear from Eqs. (2) and (3) that the meanings of structure and intensity effects are highly dependent on the activity indicator chosen. For example, energy intensity is measured in terms of energy consumption per household in Eq. (2) while it is measured in terms of energy consumption per unit floor area in Eq. (3).

Eqs. (2) and (3) share the basic assumptions of homogeneous ownership of household appliances and similar consumption behaviour for the same housing type. The two identities are reasonable if households can be meaningfully and conveniently divided into homogeneous housing segments. This condition apparently cannot be easily met in most countries and the

[2] For conciseness, the fuel emission factor is not considered in Table 2. Interested readers can refer to the original publications for all the factors included in the decomposition identity.