The “Screening Index” to Select Building-Scale Heating Systems

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Abstract. Buildings are increasingly considered as a key to de-carbonize the economy, with improvements in their energy efficiency and in their heating systems as primary targets. The heating systems have a moderate lifespan, are renewed more frequently, and the integration of renewable energy sources is increasingly important. The energy selecting problem is a strategic issue. Several parameters should be included in the decision making such as technology, economy, environment, social benefits and others. An objective and quantitative decision is essential to select the optimal heating schemes. To develop such multi-criteria assessment, the present study combines the improved AHP and grey relational TOPSIS, together with the use of linear and non-linear combination weighing. It results in a quantitative comprehensive assessment, called “Screening index” model. Based on the evaluation elements, the optimal single or hybrid energy route option can be selected, as illustrated in a case study. The index can help users, system manufacturers, builders and even governments to select the most appropriate heating schemes.

1. Introduction and objectives

Buildings are increasingly considered as a key to de-carbonize the economy. Improvements in the energy efficiency of buildings and in their heating systems are primary means to achieve such decarbonisation. Although buildings themselves are of long-life duration, the energy systems have a shorter lifespan and are renewed more frequently [1]. The use of new heating and cooling utilities in buildings is of growing interest and the integration of renewable energy sources is increasingly important. This is illustrated in a review by Heiskanen and Matschoss [2] for the European developments in the field, including geothermal, solar, biomass and other renewable resources, with evident differences among countries and among the building scale. It is commonly agreed upon that fossil fuels must progressively be replaced by renewable energy sources to mitigate the effects of climate degradation [3].

As a consequence of possibly using various renewable energy resources, their evaluation is an essential issue, with current systems like Life Cycle Assessment (LCA) and/or Life Cycle Cost (LCC) often used as a single criterion analysis. The energy-selection should however be based on multiple aspects like economics, social benefits, environmental quality and energy efficiency, that do not facilitate the decision making, unless clearly expressed in a global assessment protocol.
Some researchers have developed single evaluation methods to select renewable energy sources. Zangeneh et al. [4] develop a model based on an analytical hierarchy process (AHP) for prioritization of distributed energy generation technologies and the potential of regional primary energy resources. Wang et al. [5] presented an improved grey relational method for evaluating five distributed triple-generation systems. A common shortcoming of these methods is their lack of providing a concept for the degree of excellency of energy. In reality, multi-decision is preferred rather than a single decision to avoid the bias and minimize the partiality during the process. The present research developed a screening system for different gas/solid applications [6-8]. Based on this system, the present study combines the improved Analytic Hierarchy Process (AHP) and grey relational Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), together with the use of linear and non-linear combination weighing, and resulting in a quantitative comprehensive assessment, called “Screening index”, highlighting the “decision-making” strategy, emphasizing the complex relationship between energy efficiency, social benefits, economy and environmental quality. The total index combines systematics and flexibility, albeit being of multi-objective and multi-level nature. Based on the evaluation elements, the optimal single or hybrid energy route option can be selected. The index can help users, system manufacturers, builders and even governments to select the most appropriate heating schemes.

2. Method: the “Screening index” model

The proposed model combines the AHP and grey relational TOPSIS methods and expands it into a relative ranking of a proposed heating solution in terms of a quantitative index. This model consists of five basic stages (Figure.1): (1) formulate a hierarchical structure, (2) calculate weights by AHP, (3) determine alternative heating schemes, (4) evaluate alternatives with grey relational TOPSIS, and (5) determine the final ranking according to the “Screening index”. The model development is itemized below according to each step of the model strategy.

Figure 1. Schematic diagram of the strategy mode.

The “Screening index” model firstly sets the judgment matrix by fuzzy AHP [4], and the ranking method by confidence is applied to determine the weight vector. Then the TOPSIS evaluation method [5] is improved with the grey relational theory. Finally a quantitative index is calculated in order to better rank the energy scheme. The total procedure involves 7 steps, with details previously presented by the authors [6-8].

Step 1: Construct the evaluation system according to 4 major factors, i.e. technique, economy, environment and social benefits. Then set sub-goals according to the region or specific objectives.

Step 2: Determine the weight vector of each evaluative index.
Step 3: Obtain the grey relational degree $\xi_i(j)$ between each scheme and positive or negative-ideal by using grey relational method.

Step 4: Determine the Euclidean distance $\zeta^*$ of each alternative from the positive/negative-ideal solution $D_i^*$ with TOPSIS.

Step 5: Eliminate the influence of dimensions ($\xi^*$ and $D_i^*$).

Step 6: Weighted handling of the grey relational TOPSIS.

$\zeta^* = \max_{j \in \xi^*} \left\{ \frac{\max_{l \in \xi^*} \left\{ \zeta_{lj} \right\}}{\min_{l \in \xi^*} \left\{ \zeta_{lj} \right\}} \right\}$

$\zeta^- = \max_{j \in \xi^-} \left\{ \frac{\max_{l \in \xi^-} \left\{ \zeta_{lj} \right\}}{\min_{l \in \xi^-} \left\{ \zeta_{lj} \right\}} \right\}$

Step 7: The relative degree of each scheme is ranked according to:

$C_i = \frac{D_i^-}{D_i^* + D_i^-}, 0 \leq C_i \leq 1$ (3)

3. Illustrative application

The Jing-Jin-Ji region (in China) is selected as a case, being one of the three major urban agglomerations and recognized for its heavy air pollution. To reflect the performance of different energy sources, the comprehensive “Screening index” is constructed with "14 sub-indexes ", shown in Table 1. The 14 indexes are defined in view of the current situation, demands and targets of this region. Of course different combinations of sub-indexes are possible to adapt the assessment to specific goals.

| Sub-goal       | Sub-indexes                      | Type$^a$ |
|----------------|---------------------------------|----------|
| Energy efficiency | efficiency of energy use (a11)  | Profit index |
| (A1)            | temperature distribution (a12)  | Interval-type |
|                 | degree of automation (a13)      | Profit index |
| Economy         | operating cost per unit area (a21) | Cost index |
| (A2)            | initial investment per unit area (a22) | Cost index |
| Environment     | emissions of VOCs (a31)         | Cost index |
| (A3)            | emissions of residue (a32)      | Cost index |
|                 | emissions of $SO_2$ (a33)       | Cost index |
|                 | emissions of NO$_X$ (a34)       | Cost index |
|                 | emissions of CO$_2$ (a35)       | Cost index |
|                 | emissions of Total Suspended Particulate (TSP) (a36) | Cost index |
| Social benefits | diggable energy per person (a41) | Profit index |
| (A4)            | operational safety (a42)        | Profit index |
|                 | structural compatibility (a43)  | Profit index |

$^a$ normalized decision matrix is:

$\frac{b_{ij}}{b'_{ij}} = \frac{x_{ij}}{\sum_{i=1}^{m} (x_{ij})^2}$, $i = 1, 2, ..., m; j = 1, 2, ..., n$ (for the profit index, the larger the better)

$\frac{b_{ij}}{b'_{ij}} = \frac{1}{\sum_{i=1}^{m} (x_{ij})^2}$ (for the cost index, the smaller the better)

The decision matrix is built by the pairwise comparison of 4 elements (A1 ~ A4) within the standardized scale of nine levels. The consistency is then determined with the weight vector $w$, the highest positive eigenvalue $\lambda_{max}$, the consistency index C.I, and the random consistency index R.I (All the equations are given in [6-8]). The final consistency ratio, C.R., is calculated. It is consistent according to AHP if the value is smaller than 0.1.
Similar fuzzy calculations are performed for the other alternatives and given in Table 2. The judgment matrixes are calculated. If the matrix satisfies the consistency, the weights of sub-goals and sub-indexes are synthesized into the total weights of figure 2.

**Table 2.** Indic Judge matrix of energy efficiency indexes.

|                  | \((a_{ij})_{m \times n} \) | \(w\) |
|------------------|-----------------------------|-------|
| \(A_1\) to \(A_4\) | \[
\begin{pmatrix}
1 & 1/2 & 1/3 & 2 & 0.1707 \\
2 & 1 & 1/2 & 2 & 0.2598 \\
3 & 2 & 1 & 3 & 0.4495 \\
1/2 & 1/2 & 1/3 & 1 & 0.1202
\end{pmatrix}
\] | |
| \(a_{11}\) to \(A_1\) | \[
\begin{pmatrix}
1 & 1/2 & 3 & 0.3338 \\
2 & 1 & 3 & 0.5247 \\
1/3 & 1/3 & 1 & 0.1416
\end{pmatrix}
\] | |
| \(a_{21}\) to \(A_2\) | \[
\begin{pmatrix}
1 & 2 & 0.6667 \\
1/2 & 1 & 0.3333
\end{pmatrix}
\] | |
| \(a_{31}\) to \(A_3\) | \[
\begin{pmatrix}
1 & 1/2 & 1/3 & 1/3 & 1/2 & 1/3 & 0.0678 \\
2 & 1 & 1/2 & 1/3 & 1 & 1/2 & 0.1068 \\
3 & 2 & 1 & 1/2 & 3 & 2 & 0.2345 \\
3 & 3 & 2 & 1 & 3 & 2 & 0.3156 \\
2 & 1 & 1/3 & 1/3 & 1 & 1/2 & 0.1008 \\
3 & 2 & 1/2 & 1/2 & 2 & 1 & 0.1745
\end{pmatrix}
\] | |
| \(a_{41}\) to \(A_4\) | \[
\begin{pmatrix}
1 & 4 & 4 & 0.6551 \\
1/4 & 1 & 1/2 & 0.1335 \\
1/4 & 2 & 1 & 0.2114
\end{pmatrix}
\] | |

**Figure 2.** Weights of criteria.

As illustration, five heating schemes are examined:
- Scheme 1: solar boiler with biomass as auxiliary energy supply
- Scheme 2: electric boiler with storage system
- Scheme 3: air-source heat pump system
- Scheme 4: coal-fired heating
- Scheme 5: natural gas-fired heating
In scheme 1, a flat-plate solar collector is placed on the roof, to provide 44% of the heat that the house needs in winter, the balance is supplied by biomass. In scheme 2 and 3, the electricity is supplied from a thermal power station (mainly coal-fired electricity in the region). Average data were gathered from ASHRAE [9]. The emissions for non-coal fired concepts are related to the emissions of a corresponding coal-fired power generation [10] and summarized in table 3. Operating cost and initial investment were obtained from [11].

| Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 5 |
|----------|----------|----------|----------|----------|
| efficiency of energy use (a11) | 81% | 90% | 70% | 55% | 73% |
| temperature distribution (a12) | 40-50°C | 40-50°C | 20-30°C | 40-60°C | 40-60°C |
| degree of automation (a13) | Medium 0.3 | Good 0.7 | Good 0.7 | Bad 0.3 | Good 0.7 |
| operating cost per unit area (a21) | 6.8 rmb | 48.5 rmb | 25.5rmb | 13.9 rmb | 27.2rmb |
| initial investment / m² (a22) | 270 rmb | 175 rmb | 300 rmb | 110 rmb | 330rmb |
| emissions of VOCs / m³/d (a31) | 0.06kg | 0.68kg | 1.47kg | 0.31kg | 0.07kg |
| emissions of residue/ m³/d (a32) | 116.9g | 195.2g | 56.3g | 203.3g | 0g |
| emissions of SO₂/ m³/d (a33) | 0.06kg | 1.26kg | 2.72kg | 0.57kg | 0.12kg |
| emissions of NOX/ m³/d (a34) | 0.12kg | 0.34kg | 0.74kg | 0.15kg | 0.03kg |
| emissions of CO₂/ m³/d (a35) | 0.01kg | 23.91kg | 51.51kg | 10.84kg | 2.33kg |
| emissions of TSP/ m³/d (a36) | 0.92kg | 1.54kg | 3.31kg | 0.70kg | 0.15kg |
| diggable energy per person (a41) | 846.4t | 417.4kWh | 417.4kWh | 500.2t | 4.32m³ |
| operational safety (a42) | Good 0.7 | Good 0.7 | Good 0.7 | Bad 0.3 | Medium 0.5 |
| structural compatibility (a43) | Bad 0.3 | Medium 0.5 | Medium 0.5 | Bad 0.3 | Good 0.7 |

*Heating a 189 m² room at 50 W/m². The calorific value of standard coal is 29308 kJ/kg, of natural gas 35.88 MJ/m³, and of biomass 18.7 MJ/kg. The power of the electric heating boiler with storage system is 3.2 kW, and 3.9 kW for the air-source heat pump system. rmb = Chinese currency, 1 € ~ 7.8 rmb.

Data of various items in the 5 schemes and the evaluation matrix are given in Table 4 and Table 5, respectively.

**Table 3.** The emission data based on emission factors of coal [10, 12-13].

| Pollutant | SO₂ | NOₓ | CO₂ | VOCs | TSP |
|-----------|-----|-----|-----|------|-----|
| Emission factor (kg/t-coal) | 7.4Sₐₙₐ | 2.0 | 140.1 | 4.0 | 9.0² |

²Sₐₙₐ is sulfur content on dry coal basis.

³The emission of TSP: average of 8 to 10 kg/t coal.
Further calculations are done for all schemes. The results are summarized in Table 6. Based on $C_i$ values, the ranking of the alternative schemes in descending order is Scheme 1, Scheme 5, Scheme 3, Scheme 4 and Scheme 2. The proposed model results indicate that Scheme 1 is the best alternative with a $C_i$ value of 0.59, whereas scheme 2 scores the lowest, due to the heavy environmental impact of coal firing or coal-fired power generation.

| Scheme | $D_i$  | $D_i$  | $C_i$  | Result |
|--------|--------|--------|--------|--------|
| Scheme 1 | 0.12   | 0.18   | 0.59   | 1      |
| Scheme 2 | 0.22   | 0.04   | 0.17   | 5      |
| Scheme 3 | 0.22   | 0.05   | 0.20   | 4      |
| Scheme 4 | 0.18   | 0.08   | 0.32   | 3      |
| Scheme 5 | 0.15   | 0.16   | 0.51   | 2      |

The different alternatives ($Y_1, \ldots, Y_{43}$) are taken into consideration for their role in an energy selecting strategy. Solar-biomass combined energy supply has a highest score in both economy and social benefits, and performs well in the environmental and energy efficiency aspects. Details are illustrated in Figure 3.

![Figure 3. Details of 5 house heating systems](image)

4. Discussion
The “Screening index” model of the case study is based on the comparison of identified criteria: energy efficiency, economics, environment and social benefits. In this case, the two key points are economics and environment, because “green growth” is pursued. With its 4-mentioned criteria, the “Screening index” model differs from the present energy evaluation models like LCC or LCA, since it evaluates energy by a multi-point approach.

AHP and grey relational TOPSIS compound decision making methods are used in the model. AHP is used to assign weights to the criteria to be used in scheme selection, while grey relational TOPSIS is employed to determine the priorities of the alternatives. The properties and effectiveness of a scheme are not always a linear relationship, and the grey relational method can cover the shortage by measuring the similarity of the curve’s shape. The “Screening index” model has significantly
increased the efficiency of selecting the energy routes and it transfers the fuzzy data into a quantitative decision. The “Screening index” model can be used in different ways, and can even consider the subjective requirements of the user. For example, if the screening model is used for the evaluation of the technical performance of different solar dryers [14-18], it can set economic and practicality sub-goals superior to environmental ones when using the pairwise judgment methods, hence stressing the better acceptance of a technology. Such practicality sub-goals can be the drying time, the quality of food products before and after solar drying, the energy input of re-hydration, the effect of insects and rodents, etc. Thereafter it can also play an essential role in food production and agriculture systems. Compared with other evaluation methods, the advantages of the “Screening index” model are:

- a hierarchical structure of energy criteria is set up to facilitate the energy evaluating process, relating to many aspects.
- combining the Euclidean distance with grey relational degree, it considers non-linear relationships between two indexes in addition to linear ones.
- the performance of each alternative to each criterion is defined in numerical values or in linguistic terms if the criterion is quantitative or qualitative, respectively,
- operating with trapezoidal fuzzy numbers, no cumbersome computations are required.

The method has however its own shortcomings, since it is mainly limited by the pair-wise information given by the users: the importance of different indexes has to be compared first, so it is a "soft" criterion to evaluate energy technologies. Although the mathematical algorithm can describe a comparable solution between indexes, the pairwise results are not conditioned by a very restrictive transitivity definition.

Although it is a successful tool of decision-making, some aspects could be improved such as: increasing and developing the evaluation criteria; and/or developing a model to distinguish users’ starting point since the selection of fuzzy numbers impacts the results of evaluation. Evidently, it needs adapted to the local, regional or country conditions, where e.g. coal-firing is seldom used (EU, USA) and power generation can be of nuclear or gas-fired nature and renewable electricity (wind, photovoltaic) should be considered.

5. Conclusion
The energy selecting problem is a strategic issue. Several alternatives should be considered like technology, economy, environment, social benefits and others. They are a function of many different criteria.

An objective decision is essential to select the optimal heating schemes. In this paper, the “Screening Index” assesses heating systems. The application to the selected case of house heating illustrates its potential. Using technological properties, acceptable health and safety hazards, limited environmental impact, low cost and availability in large quantities, a weighed scoring was presented. Significant differences can be observed between the 5 energy routes. The hybrid solar-biomass route is judged by far superior having the highest value of the “Screening index”.

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