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Using multi-criteria analysis to prioritize renewable energy home heating technologies

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Abstract

Replacing all oil boilers with renewable energy technologies by 2035 is part of the national energy strategy 2050 in Denmark. Individual heating is supposed to supply around one-fourth of the total residential heating after 2035. About 205,703 homes will need to replace their current oil boilers. This study investigates the drivers for decision makers when adopting different renewable heating technologies. A total of 11 factors that embrace the economical, technological and environmental aspect of the alternative renewable heating technology are identified, and these were used for the selection of the alternative renewable heating technologies. Three renewable heating technologies: solar heating, heat pumps and wood pellet boilers are used in the estimation. The multi-criteria decision making analysis shows that solar heating is considered as the best alternative, and heat pumps is the second best, wood pellet boiler is the least attractive among three alternatives. It can be noted that solar heating and heat pumps are close alternatives.

Keywords: Sustainable energy technologies for heating; Individual home heating; Multi-criteria decision making; Renewable energy technology prioritization

Introduction

The global need for energy will continue to grow as the world economies grow. Fossil fuels, such as coal, oil and natural gas, are primary contributors to the energy supply. However, the vast use of fossil fuels has brought severe environmental problems such as carbon emission, land depletion etc. Therefore, there is an urgent need for transforming the current fossil-fuel dominant energy supply to a renewable energy sources based energy supply. The Danish government has also set an ambitious target of becoming a fossil fuel independent nation by 2050 in the new *Danish Energy Agreement* [1]. A part of the current government agreement has also set the framework for the energy supply in Denmark, namely, that the supply of electricity and heating should come from renewable energy by 2035 [2]. However, the change of the energy supply from fossil fuels to renewable energy sources requires not only the expansion of renewable energy but also the appropriate use of renewable energy. Due to its geographic location, Denmark has plenty of wind power sources. In 2012, wind energy took up one third of the total energy supply. The problem associated with increasing the share of wind energy is that wind energy is erratic and weather dependent, thus, the amount of wind energy that flows into the grid varies dramatically depending on weather conditions, which makes it difficult to fully use the generated power. This is bad because fossil fuel fired power plants are still necessary for balancing the grid. Thus, the increasing amount of wind energy is a challenge for the current power system.

An emergent task therefore is to find methods that can adapt the variable power production (e.g. the intermittent wind power). The potential of biomass to replace fossil fuels is limited, both seen from the global and national perspective. The other two often mentioned solutions for getting a balanced grid are batteries (i.e., large-scale electricity storage technology) and “smart grid” technology. Large-scale electricity storage is about to store electricity in the off-peak period and to feed power to the grid in the peak period. Smart grid is about using an information technology system to adjust the behaviors of suppliers and consumers in an automated fashion to increase efficiency, reliability, economics and sustainability of the energy system [3], [4].

In Denmark, energy used in the building sector accounts for about 42% of total energy consumption [5]. Space and water heating in the residential sector is an important entry in the final energy consumption statement. Large cities and towns have developed well-established city-wide heating networks over the past decades. Heat is mainly produced by large coal- or gas-fired CHP (Combined heat and power) plants as well as waste incineration CHP plants in Denmark [5]. The heat supply configuration in the future in Denmark will be a combination of district heating in areas with high population density and individual heating in areas with low population density [6]. A district heating network that can cover about 55% of the heat consumption is more economic feasible than 100% coverage given substantial heat saving measures are installed [7]. This is because the evaluation of the efficiency of district heating should not only be evaluated in monetary terms but also take into account socio-economic and environmental influence [7]. Following the national energy strategy 2050, all individual heating must be produced by renewable energy technology [6]. According to COWI [8], there are about 205,703 homes that have the technological potential to replace their current oil boilers with heat pumps in Denmark. The need of energy for space heating for these homes is about 3.9 TWh per year. Fig. 1 displays the geographic distribution of the heat supply in Denmark. In this map, orange colored areas are large cities with central heating plants (CHP), green colored areas are provincial towns with district heating, blue colored areas are regions with individual natural gas boilers, and areas without circles are rural areas without any public heat supply. For areas without any public heat supply, oil boiler is the main heating method, thus, these areas are the primary target market for heat pumps. It is obvious that homes with oil boilers are mainly scattered in remote rural areas [8]. A collective heating system is difficult to connect to these regions because the cost for building the infrastructure is too high.

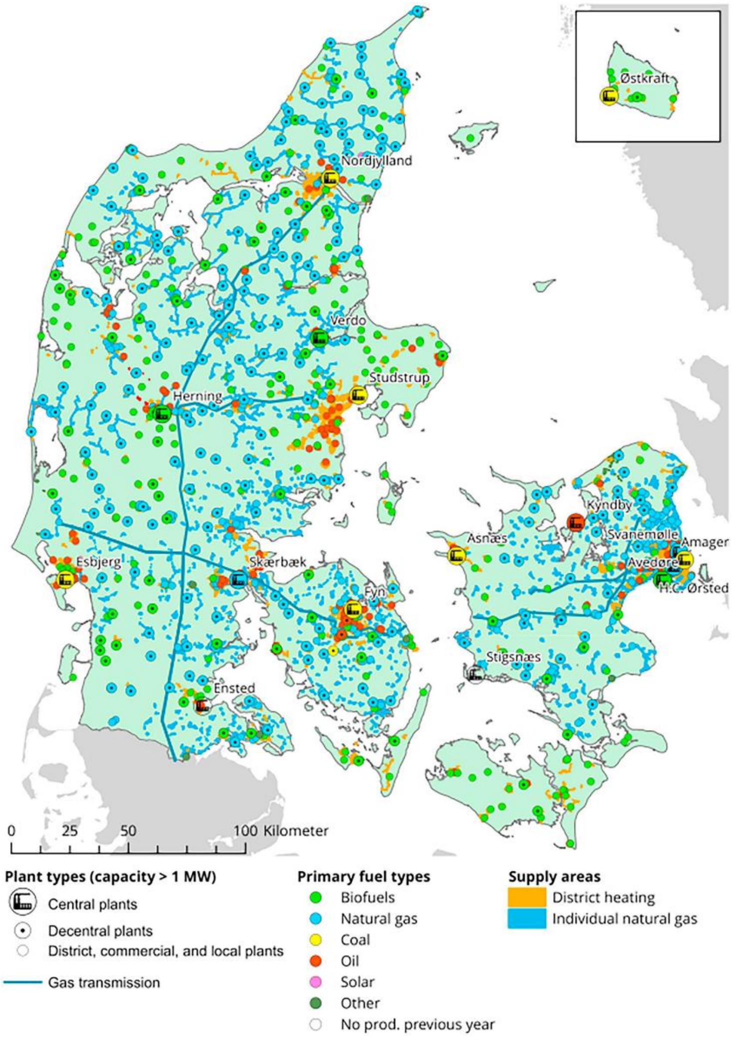

Fig. 1. Geographic distribution of public heat supply in Denmark. Source: Danish Energy Agency [49]

There are several renewable energy technology alternatives for replacing the current oil boiler in the market: heat pumps, solar panels and wood pellet boilers. Heat pumps, known as "varmepumper" in Danish, has three major formats in the current market, air-to-air, air-to-water and water-to-water heat pumps in the market. Each type of heat pumps has its own advantages and drawbacks. For more information about these three types of heat pumps, please refer to Appendix A. The water-to-water and air-to-water heat pumps, are often seen as an appropriate energy technology that can help improve the use of wind power [9], [10]. This is because heat pumps can function as a "battery" to store electricity in the form of heat [11]. Furthermore, when there is excess of wind energy, the price of electricity is low, thus, heat pumps are also economically attractive. Table 1 shows that the installation of individual heat pumps in single-family houses and town houses/terraced houses can bring a substantial reduction on energy consumptions. Finally, electricity is high-quality energy and must be used for electricity-specific energy consumption. Thus, the use of heat pumps can amplify the value of electricity, in other words, increase the energy efficiency [12]. Precisely, when heat pumps use electricity to compress a low temperature to a high temperature through a refrigerant circuit system, every one kWh of electricity used by the heat pumps can produce about 3.5–5.5 kWh of heat [13]. Therefore, the integration of heat pumps in an energy system with large amount of wind energy does not only bring environmental benefits such as reducing CO_2 emission but also increase the flexibility in the energy system. In this study, we refer to heat pumps as water-to-water heat pumps because this type of heat pumps can contribute to the integration of wind power, reduction of environmental emissions and the total system costs [6]. When considering further environmental impact, individual heat pumps may be preferable from a climate viewpoint [13], [14].

Table 1. Potential savings from use of individual heat pumps instead of fossil-fuel boilers (in GWh)

Building and dwelling categories	Current annual heat consumption (with oil boilers)	Future projected annual heat consumption (with heat pumps)
Single-family house	20,900	6800
Town house/terraced house	2500	815
Holiday homes	725	295

Source: Jensen, Hvenegaard [46].

Note: The estimation is based on the total area of each building and dwelling category currently using oil boilers from the Building and Dwelling Registration (BBR) and the average heat consumption per square meter for each category.

The second renewable energy technology alternative for replacing oil boilers is solar heating. Solar is a free and abundant energy resource on earth. The major constraint of solar heating is the solar radiation availability. Denmark especially the Jutland Peninsular has a moderate suitability for solar photovoltaic systems [15]. It is estimated that solar thermal collectors in Denmark has an average solar radiation value of 5.1 kW hours per square meter per day (kWh/m2·day) [16]. In 2015, about 605 GWh electricity was generated from solar photovoltaic cells, which corresponds approximately to 2% of the Danish electricity consumption [17]. Following the estimation method by Hagos, Gebremedhin [12], this is equivalent to a reduction of 52,156 tons of oil energy and 161.6 kt CO2 emission. Thus, the diffusion of solar energy can contribute greatly to the emission target. Solar collectors and the water tank transfer the heat to the home heating and hot water system, see Fig. 2.

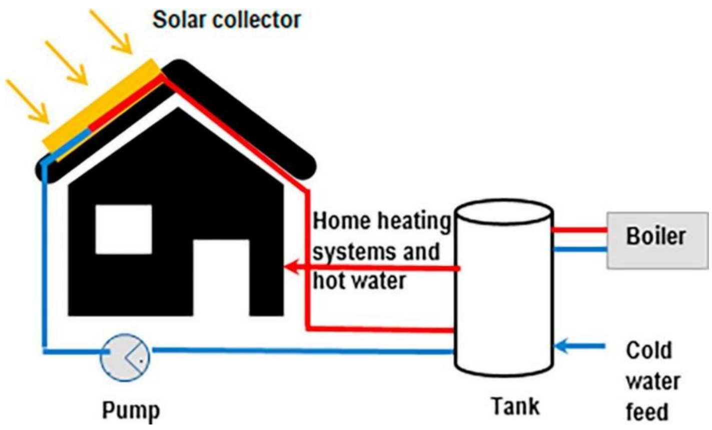

Fig. 2. A simple illustration of solar thermal for home heating systems

Finally, wood pellet boilers for space heating in private dwellings is also considered as another alternative for replacing oil boilers. Due to the limited self-supply in wood pellet, the share of individual wood pellet boilers remains almost constant [18]. Although wood pellet boilers use renewable energy sources, burning wood pellet can generate small particles and nitrous oxide etc., which pose a hazard for human health and for the environment [19], [20], [21].

To promote the diffusion of renewable energy technologies to substitute oil boilers, energy regulators and planners have made many efforts, e.g., subsidies for the installation, tax reduction on the labor cost of installation, discount on the electricity tariff for heat pump owners (i.e., 50 øre[1] per kWh discount on electricity consumption). In addition, many R & D projects such as the project "from wind to heat pumps" was launched to investigate the technological potential of integrating a large share of wind power [22]. However, there have been slow penetration of the different individual renewable heating technologies [13]. As of 2010, only approximately 10% of the potential customers have replaced their oil boilers by either water-to-water or air-to-water heat pumps, and the annual sales of these two types of heat pumps is between 4000 and 5000 sets [23]. This is unfortunate, because the government wants all individual oil boilers to be replaced by renewable energy based heaters such as heat pumps by 2030 [2]. Eventually, this can be a hurdle for achieving the goal of being a 100% renewable energy across all sectors by 2050. Furthermore, there is a lack of studies on understanding how renewable energy technology such as heat pumps will develop using a socio-technical approach [13].

Given this, the objectives of this study are to investigate the barriers for replacing current individual oil boilers with renewable heating technologies and to investigate how these different renewable energy technologies will be prioritized in the decision-making. The research setting is in the Region of Southern Denmark. There are several reasons for conducting this study in the Region of Southern Denmark. Firstly, there is a big market potential for the renewable energy technologies within the territory. According to the estimation by COWI, there are about 48,956 homes in the Region of Southern Denmark with oil boilers [8]. Secondly, there is an increasing share of wind power capacity, both land and offshore wind power in the Region of Southern Denmark, but the demand for energy remains almost constant over past years. Encouraging new renewable energy technologies that can help exploit periods with maximal wind production to replace the current oil boilers is one of the recommendations for achieving a 100% fossil fuel independent nation by the Danish Climate Commission [24].

The paper is organized as follows. Section "Methodology" describes the TOPSIS model for decision making. Section "Result" presents the study results followed by a sensitivity analysis. Section "Conclusions and policy implications" is the conclusion and discussion, and possible directions for future work are also presented.

Methodology

Criteria selection in renewable energy technology decision making

Multicriteria decision-marking is a decision support approach that have been widely applied in evaluating renewable energy technologies, renewable energy planning and policy and renewable energy product selection [25], [26], [27]. In this section, a literature survey aiming at a review of criteria applied for energy technologies assessment was conducted.

Renewable energy technology is new to oil boiler home owners. Thus, the adoption of renewable energy can be seen as adoption of an innovation. One of the well-known theoretical frameworks is innovation diffusion. Rogers [28] suggested that the diffusion of innovation follows an S-curve over time. A typical innovation process initiates from individual awareness, then go through interest to judgment, desire to trial and eventual adoption [28]. Therefore, the adoption process can be considered as a decision making process for adopters and it is influenced by four critical elements: (1) the novelty of the innovation, (2) communication among individuals, (3) time and (4) social influences [28]. The diffusion rate is largely dependent on five key characteristics of the new product, namely (1) perceived relative advantage of the innovation as compared to existing alternatives, (2) consistency with existing values, potential needs and experiences, (3) perceived complexity to understand and use the innovation, (4) possibility to try the innovation, and (5) visibility to others. Among these characteristics, the perceived advantage and comparability are recognized as the most important [28]. According to Rogers, "relative advantage" is "a ratio of the expected benefits and the costs of adoption of innovation" [28].

Wang, Jing [25] summarized a number of criteria for evaluating energy-related projects and policies published in previous multi-criteria decision making analyses (MCDA) based on an extensive literature review. These criteria can be classified into four aspects: technical, economic, environmental and social [25]. A pre-condition for the selection of a certain renewable energy technology to substitute the oil boilers is that the new renewable energy technology should be superior in terms of the technical, economic, environmental and social aspects. Next, we will focus on identifying indicators from previous studies with a special focus on renewable home heating technologies.

The economic dimension is the main driver for the diffusion of renewable energy technologies [29]. In an experiment on assessing households' preferences for different home heating technologies in the UK, six criteria that has a range from 1 to 5 were identified [30]. These are: type of heating system, total installation cost subsidiary, annual maintenance cost, annual fuel bill, annual payment given to householder and number of years householder receives annual payment [30]. IEA-SHC [31] pointed out that cost of renewable home heating technology can be measured by the initial investment cost, operating cost and maintenance cost. Scarpa and Willis [32] found that *the energy(fuel) costs* and *the cost of the new boiler* are the top two important factors that influence consumers' decision to choose different heating technologies. Mahapatra and Gustavsson [33] used three indicators for assessing the economic dimension of residential home heating technologies: annual cost, investment cost and the market value of the home. With respect to the renewable energy heating technology, we decided to use "reduced energy bill", "reduced energy expenses", "low initial investment", "short payback period" and "subsidy" as indicators for assessing the economic dimension of renewable heating technologies.

Understanding the technological nature of the renewable energy technology is another important dimension. The technological advantage of a renewable heating technology, namely its performance (short heating time) is an important technical indicator. Technical complexity of a heating system is found to be an important barrier for its penetration in the market [31]. Easy to use and few reparations were used for assessing the technical complexity. Reliability was another often used factor in assessing different renewable energy technologies [31], [33].Thus, we select "high performance (short heating time)", "few reparations", "reliable" and "easy to use" as indicators for assessing the technical dimension of renewable heating technologies.

GHG emissions is the most used indicator under the environmental dimension [33]. Environmental benignity is also used to evaluate the environmental aspect of the renewable energy technology [33]. Since the integration of wind power by the substitute heating technology is an important guideline for the policy of replacing the oil boilers, we therefore include "use of renewable energy (mostly wind)" as another indicator for the environmental dimension. This criterion fits specifically into the Danish context, where there is a high proportion of wind power.

Table 2 summarizes a total of eleven indicators that are described in previous studies to assess the renewable energy technology for home heating. Table 3 presents the linguistic variable for assessing the renewable energy heating technology.

Table 2. The criteria for renewable energy heating technologies

Factors	**Criteria**	**Abbreviation**	**Information sources**
Economic	Reduced energy bill	EO_1	[8], [23], [30], [31]
	Reduced operating expenses	EO_2	[8], [23], [30], [31], [33], [47]
	Low initial investment	EO_3	[13], [23], [30], [31], [33], [47]
	Short payback period	EO_4	[13], [23], [30], [31]
	Subsidy	EO_5	[13], [23], [30], [31], [42]
Technical	High performance (short heating time)	T_1	[8], [23], [31], [47]
	Few reparations	T_2	[8], [23], [31], [47]
	Reliable	T_3	[8], [23], [29], [31], [33], [47]
	Easy to use	T_4	[8], [13], [23], [31]
Environmental	Reduction of greenhouse gas emission	EN_1	[8], [13], [23], [29]
	Use of renewable energy (mostly wind)	EN_2	[8], [13], [23], [48]

Table 3. Linguistic variable for assessing the renewable energy heating technologies

Linguistic term	**Abbreviation**	**Scale**
No influence	N	0

Linguistic term	Abbreviation	Scale
Extremely low influence	EL	1
Moderately low influence	ML	2
Medium influence	M	3
Moderately high influence	MH	4
Extremely high influence	EH	5

Determining the weight of each criterion

The equal weights method and the rank-order weights are two common methods that have been applied in sustainable energy decision making [25], [26], [29]. In a multi-criteria decision-making analysis, decision makers provide judgments on criteria and attributes of the alternatives [34]. In the first stage of this study, 18 experts who are currently working within the HVAC (i.e. heating, ventilation and air-conditioning) sector were asked to evaluate the performance of each alternative on the chosen criterion. All experts had experience with heat pumps previously, but they also had extensive special knowledge and experience about other renewable energy technologies for residents. Following Hwang and Lin [35], the use of expert judgment is useful for modeling decision-making. This method thus has been applied in solving multi-criteria decision-making problems [36]. Then, answers from the experts were then synthesized. In this study, equal weights for stakeholders were adopted in the process of synthetization [37]. Thus, the synthetized weight of each criterion can be computed by Eq. (1) below.

$$w_j = \frac{Averag\,e_j}{\sum_{n=1}^{11} Averag\,e_n} \tag{1}$$

where Average_j represents the average quantitative data for a criterion.

Proritizing the sequence of each alternative – TOPSIS method

The algorithm of the TOPSIS method is present according to Hwang, Lin [38] and Huang and Huang [39].

Assume there are m alternatives and n criteria in each alternative, the traditional decision-making matrix is shown in Eq. (2).

$$R = \{x_{ij}\}, (i = 1, 2, \ldots, m;\ \ j = 1, 2, \ldots, n) \tag{2}$$

x_{ij} represents the weight of the *j*-th criterion in the *i*-th alternative.

If a criterion benefits the alternative by increasing its value it is called a positive criteria (P), otherwise, it belongs to the negative criteria (N).

To the positive criterion j, its ideal point M_j^{ideal} can be obtained by Eq. (3)

$$M_j^{ideal} = \max(x_{ij}), (i = 1, 2, \ldots, m; j \in P) \tag{3}$$

To the positive criterion *j*, its anti-ideal point $M_j^{anti-ideal}$ can be obtained by Eq. (4).

$$M_j^{anti-ideal} = \min(x_{ij})\ (i = 1, 2, \ldots, m; j \in P) \tag{4}$$

To the negative criterion j, its ideal point M_j^{ideal} can be acquired in Eq. (5).

$$m_j^{ideal} = \min(x_{ij})\ (i = 1, 2, \ldots, m; j \in N) \tag{5}$$

To the negative criterion *j*, its anti-ideal point $M_j^{anti-ideal}$ can be acquired in Eq. (6).

$$m_j^{anti-ideal} = \max(x_{ij})\ (i = 1, 2, \ldots, m; j \in N) \tag{6}$$

In order to compute more conveniently and effectively, the normalization method can be utilized to normalize all the data, as shown in Eqs. (7) and (8).

To the positive criterion *j*:

$$y_{ij} = \frac{x_{ij} - M_j^{anti-ideal}}{M_j^{ideal} - M_j^{anti-ideal}} \quad (\mathrm{i} = 1, 2, \ldots, \mathrm{m}; \mathrm{j} \in \mathrm{P}) \tag{7}$$

To the negative criterion

$$y_{ij} = \frac{M_j^{anti-ideal} - x_{ij}}{M_j^{anti-ideal} - M_j^{ideal}} \quad (\mathrm{i} = 1, 2, \ldots, \mathrm{m}; \mathrm{j} \in \mathrm{N}) \tag{8}$$

Then, the processed decision-making matrix can be acquired, as shown in Eq. (9).

$$R' = (y_{ij})_{m \times n} \tag{9}$$

The ideal point (ideal best scheme) can be acquired with Eqs. (10) and (11).

$$Y_j^+ = \{\max(y_{ij})\} \quad (i = 1, 2, \cdots, m) \tag{10}$$

$$Y^+ = \{Y_1^+, Y_2^+, \cdots, Y_n^+\} \tag{11}$$

The anti-ideal point can be acquired in Eqs. (12) and (13).

$$Y_j^- = \{\min(y_{ij})\} \quad (i = 1, 2, \cdots, m) \tag{12}$$

$$Y^- = \{Y_1^-, Y_2^-, \cdots, Y_n^-\} \tag{13}$$

If the sample approaches the ideal point and is far away from the anti-ideal point, the sample will be more superior, Minkowski distance methodology can be used to measure the distance from the *i*-th alternative to the ideal point and anti-ideal point, as shown in Eqs. (14) and (15), respectively.

$$D_i^+ = \left\{ \sum_{j=1}^{n} \omega_j (y_{ij} - Y_j^+)^p \right\}^{1/p} \tag{14}$$

$$D_i^- = \left\{ \sum_{j=1}^{n} \omega_j (y_{ij} - Y_j^-)^p \right\}^{1/p} \tag{15}$$

Where D_i^+ represents the distance from the i-th alternative to the ideal point, D_i^- represents the distance from the *i*-th alternative to the anti-ideal point, ω_j represents the weights of criterion j (determined in Eq. (1)), p represents exponential coefficient taking value 2 in this paper.

The closeness coefficient is defined in Eq. (16), it indicates the distances between the sample to the ideal point (D_i^+) and to the anti-ideal point (D_i^-). As a rule of thumb, the bigger the first coefficient is, the better performance from the sample will be.

$$C_1^i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{16}$$

Where C_1^i represents the first closeness coefficient.

Result

The weight of each creterion

Table 4 presents the synthesized weights of the eleven criteria.

Table 4. The weights of the eleven criteria

Criteria	**EO_1**	**EO_2**	**EO_3**	**EO_4**	**EO_5**	**T_1**	**T_2**	**T_3**	**T_4**	**EN_1**	**EN_2**
Weights	0.096	0.092	0.099	0.089	0.086	0.094	0.094	0.096	0.102	0.075	0.079

The sequence of each alternative

Since the 11 criteria in this study all belong to the positive criteria, by conducting Eqs. (2), (3), (4) and Eq. (7), the original decision-making matrix in Table 5 should be converted into the processed one for further TOPSIS analysis, as shown in Table 6.

Table 5. The original decision making matrix

	EO_1	EO_2	EO_3	EO_4	EO_5	T_1	T_2	T_3	T_4	EN_1	EN_2
Heat pumps	3	3	1	1	3	3	4	3	4	4	4
Solar heating	3	4	1	2	2	5	4	2	2	5	5
Wood pellet boilers	4	2	3	3	1	3	3	4	2	1	2

Table 6. The processed decision making matrix for TOPSIS

	EO_1	EO_2	EO_3	EO_4	EO_5	T_1	T_2	T_3	T_4	EN_1	EN_2
Heat pumps	0	0.5	0	0	1	0	1	0.5	1	0.75	0.67
Solar heating	0	1	0	0.5	0.5	1	1	0	0	1	1
Wood pellet boilers	1	0	1	1	0	0	0	1	0	0	0

Subsequently, by identifying the ideal point (Eqs. (10), (11)) and the anti-ideal point (Eqs. (12), (13)), the distance from the three alternatives to the ideal point and anti-ideal point can be measured using Eqs. (14), (15), respectively. Finally, the closeness coefficient with respect to each alternative can be calculated by Eq. (16). The TOPSIS result of this study as presented in Table 7 indicates that the prior sequence in the descending order is solar, heat pumps, and wood pellet boilers.

Table 7. TOPSIS result of the ideal/anti-ideal points and the closeness coefficient with respect to the three alternatives.

	D_i^+	D_i^-	C_1^i	**Rank**
Heat pumps	0.6617	0.6367	0.4904	2
Solar heating	0.6606	0.6901	0.5109	1
Wood pellet boilers	0.7875	0.6163	0.4390	3

Sensitivity analysis

To validate the robustness of the results, a sensitivity analysis was conducted. In the sensitivity analysis, we test whether our results can be valid under 12 different cases. The 12 cases represent 12 scenarios that are based on the different weight assignments to the 11 decision-making criteria. Both equal important criterion and dominant criterion are used to create the 12 cases. An equal weight of 0.0909 was assigned to all of the eleven criteria to create Case 1. From case 2 to Case 12, a dominant weight of 0.2 was assigned to a criterion, while an equal weight of 0.08 was assigned to the rest of the criteria. Specifically, in the i (i = 2, 3,…, 12)-th case, a dominant weight of 0.2 was assigned to the (i-1)-th criterion, and an equal weight of 0.08 was assigned to the other 10 criteria.

The values of the closeness coefficient with respect to these three alternatives in different cases are presented in Fig. 3. The bigger the coefficient is, the more superior the alternative will be. Fig. 3 demonstrates that solar remains the most superior option and the wood pellet boilers is the least attractive option under the majority of the established scenarios, even if the values C1iof three alternatives are sensitive to the weights of the criteria. The only exception occurs in cases 10, where a dominant weight of 0.2 was assigned to the criterion T_4 (easy to use), heat pumps appears to be more favorable than solar heating.

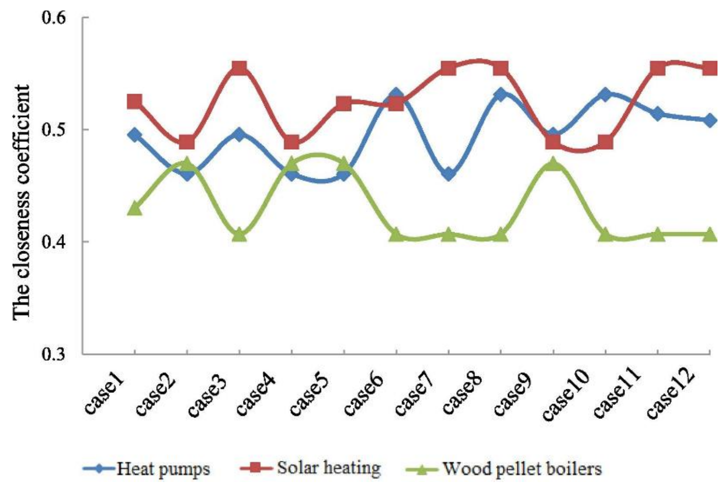

Fig. 3. Sensitivity analysis by changing the weights of the criteria

Conclusions and policy implications

Replacing the oil boilers is an important part of the national energy vision of being a fossil fuel independent nation by 2050. This study presents a multicriteria decision-making analysis to prioritize three renewable energy technologies for substituting the oil boilers. A total of eleven decision-making criteria that covers the aspects of technological, economic and environmental were identified for comparing three different renewable energy technologies. The empirical study shows that solar heating is the best, heat pumps the second best and wood pellet boiler rank the last. The results differ from a similar study conducted by Mahapatra and Gustavsson [33] in Sweden, that Swedish households prefer mostly heat pumps. Although solar heating and heat pumps are ranked as close alternatives, the result is somehow surprising and indicates that there is a need for energy policy makers to re-think the policy on using heat pumps as an integral part of green energy transition in Denmark. There are several reasons for selecting the solar thermal as the best alternative. Firstly, the price for installing a solar heating is less than half of installing a heat pump according to the Danish mechanical & electrical contractors association – TEKNIQ [40]. Houses with oil boiler are primarily scattered in the rural areas where the property price is low. Due to the specific loan ceiling of property, it is difficult for home owners with oil boilers to get a loan for a heat pump [13]. Secondly, heat pumps have a much higher heating expenses than solar heating. A heat pump consumes electricity to produce heat, but solar heating receives energy directly from the sun. In other words, the marginal cost for producing heat for solar heating is very low as compared to heat pumps. According to TEKNIQ [40], the annual electricity consumption for heat pumps is about 10,000 DKK, but the cost for solar heating is just about a few hundred DKK. Thirdly, there is a lack of policy coherence regarding heat pump. For instance, the reduced electricity tariff for heat pumps owners varies over time by the negotiation agreement between regulators and utilities [13]. Furthermore, there is generally lack of strategic and long-term vision for fiscal support on heat pumps [13]. Fourthly, the environmental contribution of solar heating is more visible than a heat pump. "When one talks about solar heat, it normally takes about two different forms, namely (1) solar energy that is collected through solar panels, and (2) solar energy that is accumulated in the ground and collected by a heat pump installing via a tube in the ground", quoted by Nyborg and Røpke [13] from a Danish VVS magazine. Furthermore, the public has difficulty in understanding how the heat pump works and its role of integrating the increasing share of wind energy [13]. With respect to last ranked alternative, a wood pellet boiler, it is more competitive than a heat pump on the price of installation, but the operating expense of a wood pellet boiler, is slightly higher than a heat pump. A major concern of selecting the wood pellet boiler lies in the environmental aspect, namely, it generates small particles and nitrous oxide etc., which pose a hazard for human health and for the environment. Indeed, the result is in line with the findings from Nyborg and Røpke [13].

However, several issues with respect to the results should be considered. First is the reliability of the solar heating. Apparently, heat pumps and wood pellet boilers are more reliable heat suppliers than solar heating. This is because solar heat is much more weather dependable. Furthermore, the seasons for home heating are concentrated in the late autumn, winter and early spring in Denmark, but the production of solar heat during these periods is limited. A plausible explanation for ranking the solar heating as the best alternative might be most of the houses with oil boilers are scattered in the rural areas and have a wood-burning stove as a supplementary heat source. A solution to the reliability problem of a single solar heating system can be combing solar and heat pumps. The campaign of "heat pumps for better use of wind power" can cause misinterpretation by the public. Due to wind energy is also weather dependent, what will happen to the heat pump if there is no wind power in the grid? Secondly, there is a current oversupply problem in the Danish electricity sector due to the increasing share of wind power. The national goal of phasing out oil boilers by 2035 is under the assumption that the renewable energy technology should help digest the over-capacity in electricity production and eventually help a shift towards a 100% fossil fuel independent nation by 2050. Although heat pump and solar heat are close alternative, the results may bring signal to policy makers on re-designing the heat pump policy.

Thirdly, the potential for achieving economic savings from the installation of renewable energy technology lies in the energy efficient level of the building [41].

There are several limitations in this research. Firstly, due to the subjectiveness and vagueness involved in judgements, the appropriateness of the decision-making suggested by the TOPSIS method combined with intuitionistic fuzzy set can be hindered. As a result, the probabilistic or fuzzy logic can be incorporated in further works to deal with uncertainty in multi-criteria decision-making problems. With respect to the weights of the decision-making criteria, further research can be extended to use the combination of entropy and ANP method. Secondly, the prioritizing decision making of this study is primarily based on the economic, technological and environmental aspect of assessing criteria. However, literature has shown that social dimensions such as attitudes towards the environment and peer communication can also influence choice of renewable energy technologies [42], [43], [44]. Further research direction may be extended to examine the social effect on the decision making. Thirdly, the current research is focused in the region of Southern Denmark, the transferability of current established model to other administrative regions in Denmark without re-estimation is unknown. Thus, further research can be extended to examine the transferability of the current model. Last but not at least, due to different economic conditions of homeowners with oil boilers, the evaluations on the economic indicators can be case-sensitive. Another direction of further research can thus be extended to investigate how socio-economic conditions will influence decision making on renewable energy technologies.

Appendix A: A brief description on different electric heat pumps

Source: Dansk Energi [45]

1. Air-to-air heat pump

The air-to-air heat pump transfers heat from outside air and releases it inside the building as hot air. The efficiency is reduced when the temperature is low. An air-to-air heat pump can be used for space heating of holiday homes and small house, or a good supplemental heating for homes with electric heating, wood-burning stove. But an air-to-air heat pump does not supply hot water. If a household wants both space heating and hot water supply, then an exhaust air heat pump is needed.

Advantage

The air-to-air heat pump can heat the rooms quickly, and switch-on and off through remote controller.

Disadvantage

The energy cost of air-to-air heat pump is very high especially because the efficiency of this type of heat pump is often lower than estimated.

Price

The price for an air-to-air heat pump is about 18.000–20.000 DKK.

2. Air-to-water heat pump

The air-to-water pump is divided into two. The outside part of the system consists of a ventilator, which takes outside air through the heat pump. The inside part is a controlling system, which is often built together with a hot water container.

Advantage

The installation of air-to-water heat pump is relatively cheap, and it does not require the “garden dug-up”. In addition, it does not need the approval from the municipality.

Disadvantage

As compare to water-to-water heat pump, the air-to-water heat pump has a lower efficiency. Air-to-water heat pump uses a bit more power than water-to-water heat pump in the cold winter. Due to the outdoor unit often makes noises, it requires an appropriate location.

Price

The price for an air-to-water heat pump is about 80.000–100.000DKK.

3. Water-to-water heat pump

The water-to-water heat pump uses the thermal energy generated and stored in the earth through pipes to heat water and space for household.

Advantage

The water-to-water heat pump is more efficient than air-to-air and air-to-water heat pumps. The technology requires few maintenance, reliable, operate fully automatically and low fuel/electricity expenses.

Disadvantage

The installation of water-to-water heat pump requires “garden dug-up” to install the piping, which means that part of the garden need to be re-built. It also needs the approval from the municipality.

Price

A water-to-water heat pump typically costs between 90.000 and 120.000 DKK.

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