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Towards Integration of Energy Storage Systems for Carbon Neutral Buildings

A Review of Multi-Criteria Decision Making Approaches

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Abstract. Building sector consumes about 40% of the global energy consumption and emits over 30% of the global energy-related CO2 emissions. It is one of the most resource-intensive sectors and the main contributor of the environmental emissions. Additionally, the amount of greenhouse gas emissions is increasing remarkably due to the rapid growth in urbanization. Distributed energy resources (DERs) offer opportunities to support the deployment of large shares of renewable energy sources (RES) in order to meet the sustainability goals of reducing carbon emissions and increasing building resilience.

DERs consist primarily of energy generation and energy storage systems (ESS) which are located near to the end-users of buildings, allowing easily integration of RES and realization of carbon neutrality. However, widespread adoption of renewable energy is challenging because of its intermittent nature. Energy supply does not satisfy with the demand, back-up supply from ESS is therefore required to solve the problems. ESS are of great importance for balancing supply and demand mismatches and offering the opportunity to replace fossil fuels with large shares of renewable penetration on DERs to eventually achieve zero-carbon emissions in buildings.

Due to numerous factors that influence ESS, selection of the suitable energy storage technologies for specific building applications presents a challenge. In the literature, different criteria have been suggested to contrast ESS' strengths and weaknesses for different applications. Methodologically, multi-criteria decision making (MCDM) has been widely employed in planning ESS. This paper aims to provide a critical review of MCDM for the deployment solutions of RES and ESS in carbon neutral building applications. A conceptual illustration is also presented to synthesize the literature review and explain the key methodologies of MCDM.

Keywords: Energy storage · buildings · multi-criteria decision making · review

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1 Introduction

As building sector accounts for about 40% of energy consumption and over 30% of greenhouse gas emissions in the world, decarbonization of buildings plays a key role in achieving climate neutrality by 2050. It is anticipated that the energy infrastructure will adopt distributed energy resources (DERs), especially renewable energy sources (RES) such as solar photovoltaic (PV), wind, and geothermal which provide decarbonisation and climate change mitigation benefits as well as building resilience against extreme weather events.

DER consists primarily of energy generation and energy storage systems (ESS) which are located near to the end-users of buildings. DER allows easily integration of RES and realization of carbon neutrality, however, widespread adoption of renewable energy is challenging because of its intermittent nature. Energys upply does not satisfy with demand, backup supply of ESS, therefore, is the key to deal with the imbalance problems.

Applications of EES to buildings have become widespread geographically depending on many influential factors, for example, specific application needs, forms and materials of energy stored, economic and environmental effects. All these influential factors will serve to make comparisons and decisions on the most appropriate technique of ESS for each type of building applications. Conflicting criteria are typical in evaluating decisions. As a result, multi-criteria decision making (MCDM) has been widely employed in planning energy storage systems. However, different MCDM approaches, criteria, goals and results for decision support are difficult to compare or to reproduce. This paper aims to provide a critical review of MCDM approaches to ESS decision support in carbon neutral building applications. A conceptual illustration of carbon neutral campus is also presented to explain the key methodologies of MCDM.

2 Overview of Energy Storage Systems (EES)

Energy storage systems (EES) are defined as equipment that can store different types of energy and convert it back into energy at later time when needed. Energy can be stored in five different forms in EES [1]: electrical, electrochemical, thermal, mechanical and chemical through charge/discharge process. In building applications, thermal energy storage (TES) is the most commonly used storage technology [1, 2] which will be the focus of this paper. The basic design parameters for TES are energy density and capacity, charging and discharging time, depth of discharge, round trip efficient etc. At the material level, heat transfer between the material and the fluid, compatibility to container material, reversible cycles, thermal losses, flexibility and modularity are the important design criteria. Besides technical requirements, TES design should also meet sustainability criteria regarding its life cycle impacts on the environment and economics with low capital and operational costs and carbon emissions. Operational strategies in life cycle of TES present essential design requirements.

A variety of TES technologies have been applied in buildings depending on the locations, capacities and costs, etc. The indicators to measure TES and building integration system are the energy load and peak reduction and savings. A major challenge of applying TES technologies is how to find the best suitable materials and technology to increase building's ability to shift energy demand away from peak periods. The answers depend on entirely on the particular building applications and the goals. In the following, both material and building level applications of TES will be reviewed.

3 Applications of Thermal Energy storage (TES)

3.1 Material Level

TES can be stored using sensible, latent heat and thermochemical energy technologies [3]. Sensible heat storage uses a high thermal mass to absorb and store heat without phase change. The stored energy is proportional to the temperature difference and the chosen materials can be solid materials (e.g. concrete and castable ceramics), liquid materials (e.g. water, oil, and sodium), and their combinations. The chosen material should have a high thermal inertia defined as the square root of the product of the thermal conductivity and the volumetric heat capacity. Water is by far the most used liquid material due to the best compromise between the cost, heat storage capacity, density and environmental impact. Figure 1 lists some examples of solid materials with their thermal inertia properties [4].

Latent heat storage systems are associated with phase change materials (PCMs) which have wide applications in buildings due to their high storage capacities within narrow temperature ranges. Building PCMs are generally categorised as organic compounds (e.g. paraffins and fatty acids), inorganic compounds (e.g. salt hydrates and metals) and eutectics [5] (Fig. 2).

Thermalchemical storage material (TCM) stores and releases heat through chemical reactions. While PCM storage systems have been beneficial for applications where heating is the main purpose, TCM storage systems can be used for both heating and cooling.. The application of PCM in cooling systems is increasing recently. Wall-integrated PCMs, for example, help to reduce daytime temperatures or ice storage can also be used very well in connection with cooling. TCM has a high storage density and is expected to have high cycling stability because the process of charging and discharging, which corresponds to desorption and adsorption of water vapor (adsorptive) on the TCM (adsorbent), respectively, is fully reversible. A comparison [6] of working temperatures for PCM and TCM applications is shown in Fig. 3.

Material	T, °C	ρ, [kg/m³]	c_p, [kJ/(kg·K)]	λ, [W/(m·K)]	$10^6\times a$, [m²/s]	$10^{-3}\times b$, [J/(m²Ks^{1/2})]
Aluminum 99.99 %	20	2700	0.945	238.4	93.3	24.66
Copper (commercial)	20	8300	0.419	372	107	35.97
Iron	20	7850	0.465	59.3	16.3	14.7
Lead	20	11340	0.131	35.25	23.6	7.24
Brick (dry)	20	1800	0.84	0.50	0.33	0.87
Concrete (aggregates)	20	2200	0.72	1.45	0.94	1.52
Granite	20	2750	0.89	2.9	1.18	2.67
Graphite	20	2200	0.61	155	120	14.41
Limestone	20	2500	0.74	2.2	1.19	2.02
Sandstone	20	2200	0.71	1.8	1.15	1.68
Slag	20	2700	0.84	0.57	0.25	1.13
Sodium chloride	20	2165	0.86	6.5	3.5	3.5
Soil (clay)	20	1450	0.88	1.28	1.0	1.28
Soil (gravelly)	20	2040	1.84	0.59	0.16	1.49

Fig. 1. Important properties of EES materials [4]

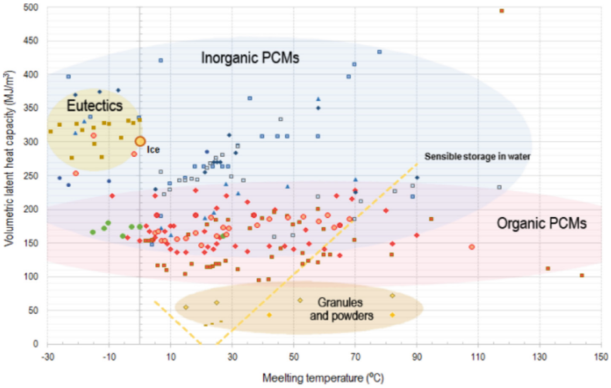

Fig. 2. Most common PCM applications in buildings and their property comparison [5]

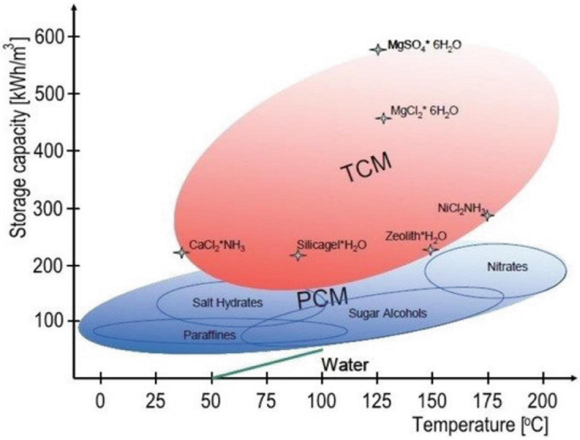

Fig. 3. Comparison of working temperatures for PCM and TCM applications [6].

Most common TCM applications in buildings and their property comparison are displayed in Fig. 4 [7].

3.2 Building Level

The current state of TES applied in buildings involves identifying opportunities for a renewable and decarbonization purposes through TES integration technologies. Broadly speaking, there are two general TES integration systems: passive and active technologies [8–10]. Figure 5 summarizes the major TES technologies in building applications [8].

3.2.1 Passive Technology

In the passive method, TES is embedded into the building construction systems, such as building envelops of walls, floors, and roofs, fenestration, and other systems in such

Material	Thermal properties		
	Charge (°C)	Discharge (°C)	Volumetric storage (MJ/m^3)
Silica gel 127B/H_2O	88	70-40	180
Zeolite 13X/ H_2O	180	55	648
Zeolite 5A/ H_2O	103	53-36	170
Zeolite 13XBF/ H_2O	150	75-47	277
Zeolite 4A/Air	180	35-10	576
Zeolite 4A/Air	180	60-35	346
	230	60-35	421
Zeolite NaX/Air	180	57	
	120	57	
Zeolite 13X/Air	120-160	70-45	
Zeolite 13X/ H_2O	130-180	65	446
LiCl salt/H_2O	46-87	30-25	911
NaOH/H_2O	95-150	70	900
NaOH/H_2O	95	32.8 or 56	
$CaCl_2$/H_2O	117-138		382-1372
LiBr/H_2O	75-90	30-40	

Fig. 4. Most common TCM applications in buildings and their property comparison [7]

way that its operation does not need auxiliary equipment. Improving thermal inertia in building envelope is an effective TES approach. PCMs are ideal materials for such a purpose. Based on the integration locations, passive technology of PCM can be classified as inside the building materials, new layers of building materials and others [9].

3.2.2 Active Technology

An active TES system, on the other hand, requires some additional energy for mechanically assisted equipment to enable the operation of TES. There are many ways to integrate TES with buildings, for example, in building envelops such as external solar facades, the ventilation system, water tanks and ground [10]. Depending on the geological locations, water tank TES, pit TES, borehole TES and aquifer TES have been widely deployed. Similar to the passive cooling, PCM is the common materials applied to active technology to increase building thermal inertia and to improve the thermal performance of TES.

3.3 Challenges and Outlooks

Since PCM usually has low thermal conductivity, PCM storage systems require complicated and expensive heat exchangers. Different thermal conductivity enhancement techniques have been proposed for PCM [11], however, this is still a challenging task. The most critical disadvantage of TCM is related to the unstable chemical compound obtained in charging period during the storing period. Although research on TCM has

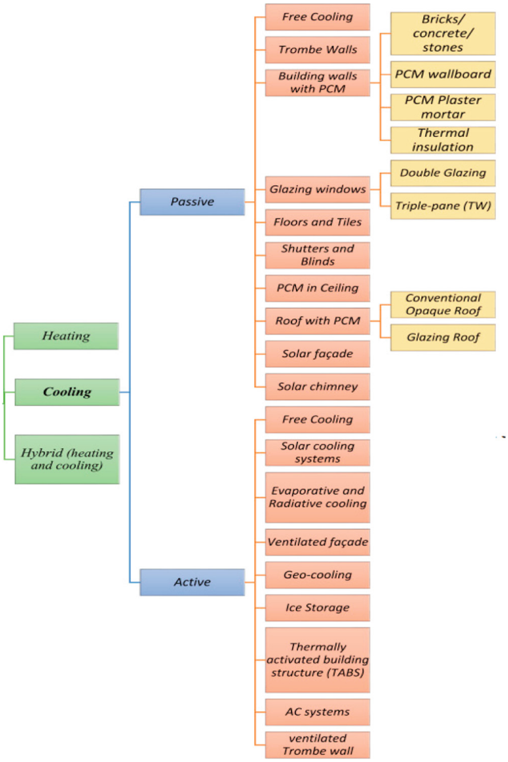

Fig. 5. Summary of the major TES technologies in building applications [8]

made some advancements, TCM remains a challenge in building applications due to its high cost [7].

Every PCM material has its own properties and qualities that contribute to the ESS overall performance. PCM used for building applications requires a melting temperature between 25–30°C for indoor comfort. Hence material thermophysical properties and costs are the key factors in determining its wide usability in the market. Since salt hydrates have been produced on a large scale, they are much cheaper than the currently available PCM in the required melting temperature range. Compared to paraffins, their volume change undergoing phase change is smaller. This property can simplify the construction of the overall storage system. Additionally, they have higher volumetric storage density than organic PCM. Therefore, low-cost salt hydrate-based thermal energy storage materials with high thermal conductivity, high storage capacity, and good thermal cycling stability present a promising PCM option in the current and future market.

4 Multi-Criteria Decision Making (MCDM)

4.1 Principles and Software

MCDM is particular useful for complex decision problems involving multiple and conflicting objectives and criteria. It provides means to compare options by assessing trade-offs between different options. Due to wide diversity of technologies in TES, selection and integration of TES requires simultaneous consideration of technical, economic, social and environmental dimensions and optimize the conflicting objectives. Figure 6 summarizes the most influential factors in the literature [12].

There are several methods for performing MCDM. The simplest way is based on a standard sweep algorithm for the constraints. This method can be computationally expensive to generate a detailed Pareto front if a large number of constraints exist. To compromise this method, a weighted sum of objectives is employed to replace constraints, unconstrained optimization can be used to generate an approximate Pareto front. More advanced methods include Analytical Hierarchical Process (AHP), genetic algorithm (GA) and other approaches to generating Pareto curve.

There are a few software tools that target at MCDM for RES [13]. HOMER (Hybrid Optimization of Multiple Energy Resources, developed at National renewable energy laboratory, USA) and iHOGA (Improved Hybrid Optimization by Genetic Algorithm, developed at University of Zaragoza, Spain) are the two popular ones.

At building level, Vallati et al. (2015) [14] optimized RES generation and TES for off-grid and then compared it with that for grid extension in terms of techno-economical and environmental factors using HOMER. TES included batteries, flywheels, and compressed air energy storage. Khan and Go (2021) [15] applied HOMER to conduct a feasibility study of power system that included large-scale ESS based on technical, economic and the demands of electricity generation in Malaysia. ESS included mixed TES and batteries.

At building material level, Ijadi Maghsoodi et al. (2020) proposed an approach for initial screening and selection of PCMs based on intervals of target values of materials' thermophysical properties, costs, and risk criteria [16]. Mukhamet et al. (2021) applied MCDM to select PCM for building envelopes based on climate factors, environmental footprint and material properties, such as thermophysical (thermal conductivity, latent

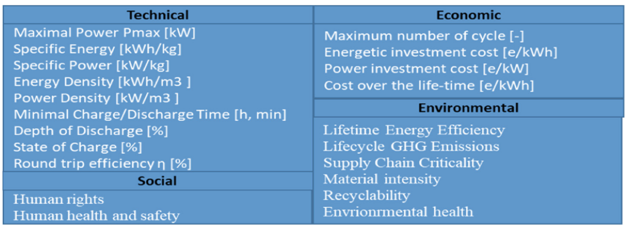

Fig. 6. Summary of the most influential factors for integrated renewable, storage and building energy systems [12]

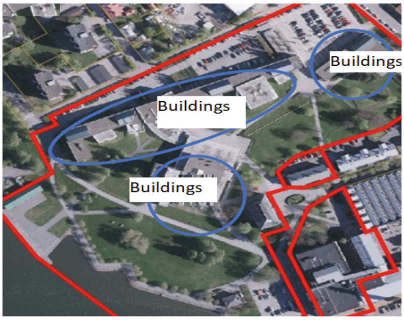

Fig. 7. Campus' layout

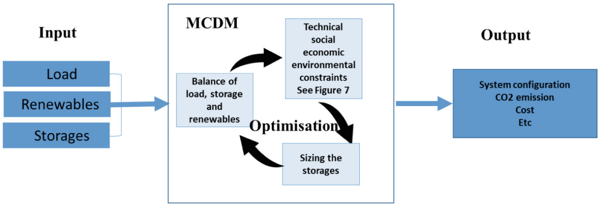

Fig. 8. Schematic diagram showing the steps applying MCDM to size the storages

heat of fusion, phase change temperature, specific heat, density, cycling stability, supercooling), economic (initial cost), chemical (toxicity, flammability, corrosiveness), and environmental (recyclability, embodied energy) [17].

4.2 Conceptual Illustration

The conceptual illustration aims to synthesize the literature review and to illustrate MCDM applied to TES investigation for carbon neutral buildings. We focus on the methodological considerations of MCDM using HOMER software. The illustrative buildings belong to university campus. Here we investigate different implementation scenarios for achieving zero carbon campus through upgrading campus' infrastructure systems (see Fig. 7). The study groups of buildings are highlighted in Fig. 7. The upgrade process takes the following steps (Fig. 8) of the analysis.

Because upgraded buildings must meet strict requirements in energy use, material selection, indoor air quality and retrofit, green building standard RTS, Finnish certification based on European standards (CEN TC 350 standards), is applied to assess the low impact development philosophy and upgrade solutions that include potential RES and ESS. As this paper focuses on ESS, we illustrate how to size ESS using MCDM.

4.2.1 Building Load Pattern

The load simulation for the buildings was performed using EnergyPlus. Collected building energy datasets on campus were used to calibrate and validate EnergyPlus model. Figure 9 displays the load patten for one building.

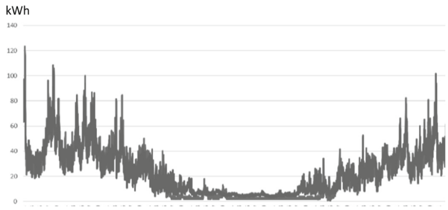

Fig. 9. Building energy consumption pattens

4.2.2 Energy System Balance Model

The RES and ESS provide energy balance to the estimated load profile (Fig. 8). Different RES and ESS alternatives and their combination are considered and assessed by MCDM, namely geothermal energy or ground source heat pump, PV radiation, recyclable waste, borehole TES (BTES), water tank storage and supplementary from district networks. Energy system models for the selected RES and ESS are constructed to balance the load demand. For example, BTES model describes how the BTES parameters, such as borehole spacing, depth, temperature and flow rate, affect the energy supply during heat injection and storage. Based on the load and the models of other energy systems, sizing of BTES can be conducted. Details of the models of energy systems are omitted due to the space limitations. For different RES and ESS scenarios, optimum configuration of TES can be selected in terms of various social, economic and environmental constraints (see Fig. 8).

4.2.3 Multi-Criteria Decision Making (MCDM)

HOMER calculates the optimum TES configuration for different energy generation scenarios. The calculation evaluates technical, economic, environmental and social factors. Currently the most common ranking technique is Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method [18]. TOPSIS method consists of the following steps: 1) Define the attributes; 2) Formulate the decision matrix; 3) Normalize the decision matrix; 4) Perform calculation on the normalized matrix. The attributes are based on the technical, economic, environmental and social factors. TOPSIS ranks the attributes to determine the option closest to the ideal solution.

HOMER simulates energy system control and constraints based on the building energy load, renewable generation, and attributes for various scenarios for a typical year 8760 h. The outputs from HOMER are optimal sizing of TES, net present cost, capital cost, and carbon emissions, etc. (Fig. 8). Figure 10 shows an illustration.

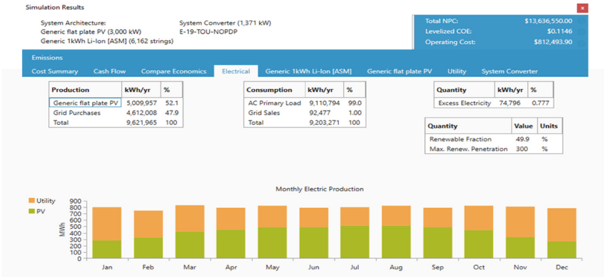

Fig. 10. Illustration of simulation result from HOMER (http://www.homerenergy.com)

5 Conclusions

This paper presents a literature review of MCDM for energy storage selection within the building sector. MCDM is an interdisciplinary approach that has been increasingly employed in applications of wide-scale RES deployment in buildings at different scales, ranging from single buildings, districts to cities. The MCDM software HOMER is introduced with a conceptual illustration.

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Authors' Contributions. All the authors presented the idea and conducted literature review. X. Lü wrote the manuscript with support from T. Lu and P. Tervola.

References

1. M.M. Rahman, A.O. Oni, E. Gemechu, A. Kumar, Assessment of energy storage technologies: A review, Energy Conversion and Management, 223, (2020), 113295.
2. K.P. Kampouris, V. Drosou, C. Karytsas, M. Karagiorgas, Energy storage systems review and case study in the residential sector, Earth and Environmental Science 410 (2020) 012033 https://doi.org/10.1088/1755-1315/410/1/012033.
3. L.F. Cabeza, Thermal energy storage, in A. Sayigh (Eds.), Comprehensive Renewable Energy, vol. 3, Elsevier, Oxford (2012), pp. 211-253.
4. R. Tamme, T. Bauer, E. Hahne, Heat Storage Media, Ullmann's Encylopedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co. KGaA, 2009
5. A. Mavrigiannaki, E. Ampatzi, Latent heat storage in building elements: A systematic review on properties and contextual performance factors, Renewable and Sustainable Energy Reviews, Elsevier, 60(C), (2016), 852–866.
6. M.M.A. Khan, R. Saidur, F.A. Al-Sulaimana, A review for phase change materials (PCMs) in solar absorption refrigeration systems, Renew. Sustain. Energy Rev. *76*, (2017), 105–137.
7. M. Schmidt, M. Linder, A Novel Thermochemical Long Term Storage Concept: Balance of Renewable Electricity and Heat Demand in Buildings, Front. Energy Res., 17 (Sec. Process and Energy Systems Engineering) (2020), https://doi.org/10.3389/fenrg.2020.00137

8. K. Faraj, M. Khaled, J. Faraj, F. Hachem, C. Castelain, Phase change material thermal energy storage systems for cooling applications in buildings: A review, Renewable and Sustainable Energy Reviews, 119, (2020), 109579, https://doi.org/10.1016/j.rser.2019.109579.
9. L. Navarro, A. de Gracia, S. Colclough, M. Browne, S. J. McCormack, P. Griffiths, L.F. Cabeza, 2016. Thermal energy storage in building integrated thermal systems: A review. Part 1. active storage systems, Renewable Energy, 88(C), (2016), 526–547.
10. L. Navarro, A. de Gracia, D. Niall, A. Castell, M. Browne, S. J. McCormack, P. Griffiths, L.F. Cabeza. Thermal energy storage in building integrated thermal systems: a review. Part 2. Integration as passive system, Renewable Energy, 85, (2016),1334–1356.
11. L.C Chow, J.K Zhong, J.E Beam, Thermal conductivity enhancement for phase change storage media, International Communications in Heat and Mass Transfer, 23 (1), 1996, 91-100. https://doi.org/10.1016/0735-1933(95)00087-9.
12. T.Balezentis, D. Streimikiene, I. Siksnelyte-Butkiene, Energy storage selection for sustainable energy development: The multi-criteria utility analysis based on the ideal solutions and integer geometric programming for coordination degree, Environmental Impact Assessment Review, 91, (2021), 106675.
13. H.Sharma, E. Monnier, G. Mandil, P. Zwolinski, S. Colasson, Comparison of environmental assessment methodology in hybrid energy system simulation software, Procedia CIRP, 80, (2019), 221-227. https://doi.org/10.1016/j.procir.2019.01.007.
14. A. Vallati, S. Grignaffini, M. Romagna, A New Method to Energy Saving in a Micro Grid, Sustainability, 7 (10), (2015) 13904-13919, https://doi.org/10.3390/su71013904.
15. M.A.M. Khan,Y.L. Go, Design, optimization and safety assessment of energy storage: A case study of large-scale solar in Malaysia, Energy Storage, 3, (2021), e221.
16. A. Ijadi Maghsoodi, S. Soudian, L. Martínez, E. Herrera-Viedma, E.K. Zavadskas, A phase change material selection using the interval-valued target-based BWM-CoCoMULTIMOORA approach: a case-study on interior building applications, Appl Soft Comput, 95 (2020), 106508.
17. T. Mukhamet, S. Kobeyev, A. Nadeem, S.A. Memon, Ranking PCMs for building façade applications using multi-criteria decision-making tools combined with energy simulations, Energy, 215 (B), 2021, 119102. https://doi.org/10.1016/j.energy.2020.119102.
18. C.L. Hwang, K. Yoon, K. Multiple Attribute Decision Making: Methods and Applications. New York: Springer-Verlag, 1981.