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Energy trilemma based prioritization of waste-to-energy technologies: Implications for post-COVID-19 green economic recovery in Pakistan

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ABSTRACT

As lockdown eases, economic activities resume in Pakistan. If the country continues to follow business-as-usual (BAU) then it is anticipated that carbon output could surge past pre-COVID-19 levels – that means more disasters in future. Thus, it is an unprecedented opportunity to shift from BAU and achieve carbon-neutral and nature-positive economic recovery – green economic recovery (GER). To fuel the GER, access to modern, equitable, affordable and sustainable energy is paramount. This study explores waste-to-energy (WtE) as an alternative green fuel for GER. Seven WtE technologies are prioritized based on the concept of energy trilemma – energy security, energy equity, and environmental sustainability. For the evaluation, an energy trilemma based decision support framework is developed using most prominent multi-criteria decision-making (MCDM) methods. The fuzzy set theory is integrated with MCDM methods to minimize uncertainty in results. Sixteen experts are engaged to score each WtE technology with respect to every energy trilemma dimension and sub-dimension. Gasification technology is found to be the most feasible option for WtE generation in Pakistan whereas Torrefaction technology is least favorable. It is concluded that the need to shift towards sustainable energy is more than ever to limit the carbon emission and prevent future crisis.

1. Introduction

While rampaging the entire world, COVID-19 also offers a watershed opportunity to rebuild a sustainable, low-carbon, and resilient world that can valiantly withstand any accidental stress, rather than buckling under it. Most importantly, developing countries must make a wise move to exploit this silver lining chance to rebalance their relationship with nature. As, tragically, these countries are likely to suffer more catastrophic impacts due to being equipped with fewer resources compared to the developed world. Those countries who do not grab it shall squander this great opportunity of reinforcing resilience into their economies and ecosystems. Similarly, Pakistan has to reoxygenate its economy sustainably amidst mounting COVID-19 tally that hitherto soars to about 0.3 million cases across the country.

Moving ahead, Pakistan shall have two pathways for recovering and restabilizing the economy. One that was already ubiquitous before the pandemic – henceforth shall be termed as business-as-usual (BAU). While the other is a transformative pathway – shall also be termed as green economic recovery (GER). In the former pathway, economic development is attained by exploiting and degrading the natural system. Mounting levels of greenhouse gases (GHGs) emission, deforestation, resource depletion, wildlife and biodiversity loss, and waste generation are some of the whammies of the BAU pathway (Shah et al., 2019a). Whereas, the latter pathway puts green and sustainable solutions at the core of economic recovery to stimulate carbon-neutral economic development (Ikram et al., 2019). It ushers in new policy levers which are congruent with Sustainable Development Goals (SDGs) and help

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reduce stress on nature, meet climate targets, as well as stave off future global pandemics (Musaad et al., 2020).

Economic recovery through both these pathways requires adequate energy support (Xu et al., 2019a). However, unlike the BAU pathway, securing energy is not only the single element required to simulate GER; production and fair distribution of energy across the population are equally important. In other words, the energy that underpins GER must conform to all three aspects of energy trilemma (energy security, environmental sustainability, and energy equity). To ensure universal access to adequate and affordable energy without straining the environment is the key motive behind the concept of the energy trilemma. The concept triggers a transition from conventional energy sources (coal, oil, and gas) towards renewable energy (RE) sources (wind, solar, biomass, solid waste, and geothermal) (Shah and Solangi, 2019). RE being the ingredient of GER can help reverse environmental damages while providing fuel to drive the economic growth as well as contributing to targets of SDGs 7 and 13.

Opting the GER pathway is a pressing need for Pakistan since the country lacks the strength to sustain drastic impacts that the BAU pathway can lead to (Shah et al., 2018). The threat of climate change is already looming over the country as it comes among the five topmost climate-vulnerable countries in the world (Xu et al., 2019b). Moreover, not only do we require to head off future climatic threats but we also need to reverse the damage that has already been done to the environment. It is a fact that conventional energy supplies compound GHGs emission and using them further might inflict an indefinite and irreparable damage to the climate (Shah and Longsheng, 2020). Whereas, in the current backdrop, interfering with the climate must be the least-priority anthropogenic action. Also, conventional energy sources were never adequate to meeting the energy demand in the pre-COVID normal days, let alone in this time of crisis. Hence, GER pathway fueled by energy trilemma based RE should be the priority choice for taking a leap forward.

At this juncture, energy experts have a pivotal role to play in guiding the government to secure RE supply so that energy shortage should not interrupt the drive for a healthy economic recovery. In this regard, this study particularly focuses on how the government can utilize solid waste to produce additional green energy for fueling the GER in Pakistan. By focusing on waste-to-energy (WtE) option, there is no any negation of the contribution other richly available RE sources can play to produce RE. But, given this public health emergency situation, the WtE option outclasses other RE generation alternatives. Because, besides producing RE and reducing GHG emissions, WtE also helps in getting rid of the alarmingly increasing solid waste which expedites the spread of infectious diseases and epidemics. It is reported that waste-borne diseases kill nearly five million people every year in Pakistan (Korai et al., 2016). Most importantly, cleaner cities are relatively more resilient in stemming the pandemic from upending lives.

The WtE technologies have emerged as a sustainable waste management and RE generation options. The widespread types of these technologies are Incineration, Gasification, Pyrolysis, Fermentation, Anaerobic Digestion, Torrefaction, and Hydrothermal Liquefaction (Khan and Kabir, 2020). Studies on WtE generation in Pakistan convey that the unprecedented level of waste generation in the country offers massive feedstock for WtE power plants. And if the government used this technology, there would be no any need to import fossil fuels for electricity generation (Siddiqi et al., 2019). It should be reminded that the aim is not only to eliminate fossil fuels but to steer toward implementing energy trilemma. In this respect, we propose an energy trilemma based decision support framework that shall help to determine which WtE technology can have greater contribution to the aim.

The framework shall evaluate WtE technologies from energy trilemma dimensions and sub-factors having different characteristics. For the evaluation, multi-criteria decision-making (MCDM) models have been applied as these models are considered best to solve multifactor decision-making problems (Shah, 2019). A range of MCDM models are available however we integrated the decision making trial and evaluation laboratory (DEMATEL), the analytical network process (ANP), and the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) methods. Although MCDM methods offer best ways to evaluate problems, using crisp values to reach a decision receives vast criticism (Muhammad et al., 2020). In solving real world problems, crisp values are often inadequate as they tend to have an uncertainty factor. Therefore, the fuzzy set theory introduced by (Zadeh, 1978) is integrated with all three models used in this study. The fuzzy set theory introduces triangular fuzzy numbers (TFNs) which are more proficient than crisp numbers in handling uncertainty (Zhuo et al., 2020).

2. Proposed decision support framework

The proposed decision framework comprises three steps as presented in Fig. 1. The initial step undertakes literature survey to build a criteria base under each dimension of energy trilemma. Experts' opinions were taken for the finalization of criteria. Similarly, WtE alternatives were sorted out keeping in view their applicability in Pakistan. Later, methodologies such as fuzzy DEMATEL, fuzzy ANP, and fuzzy VIKOR are described. Finally, the computational steps of proposed methodology are explained in which fuzzy DEMATEL is applied to determine the inner dependence within energy trilemma dimensions and within the criteria under each dimension; fuzzy ANP finds out outer relationships among criteria and computes weights of criteria that shall be used in fuzzy VIKOR to rank the alternatives.

2.1. *WtE alternatives for evaluation*

Current WtE technologies can broadly be categorized into three groups such as Thermal (Incineration), Thermochemical (Gasification, Pyrolysis, Plasma Treatment, and Torrefaction), and Biochemical (Fermentation, and Anaerobic digestion as can be seen in Fig. 2). Thermal technologies directly convert waste into heat energy while rest of the technologies initially transform waste into secondary energy carriers and then convert it into heat energy and/or electricity. The transformation of waste into secondary energy fuel enables a comparatively more efficient and cleaner energy generation process. A brief overview of these technologies follows in subsequent subsections:

2.1.1. *Thermal*

2.1.1.1. Incineration (A-1). Waste incineration is an oxidative combustion of waste in an incineration aiming to produce thermal energy while simultaneously discarding pathogenic waste under emission control. It is an effective alternative to landfill and can potentially reduce 90% of waste volume. Waste incineration is one of the commonly applied waste management practices. The thermal energy it produces can be used for heating and/or electricity generation (Panepinto and Genon, 2012). Although waste incineration appears as a simple alternative, many factors can complicate its development. For instance, the technology's high capital as well as operations and maintenance costs impede its installation as energy recovery option on large-scale (Rozenberg, 2013). Also, without proper design and execution, waste incineration can generate hazardous emissions such as furans, dioxins and other heavy metals.

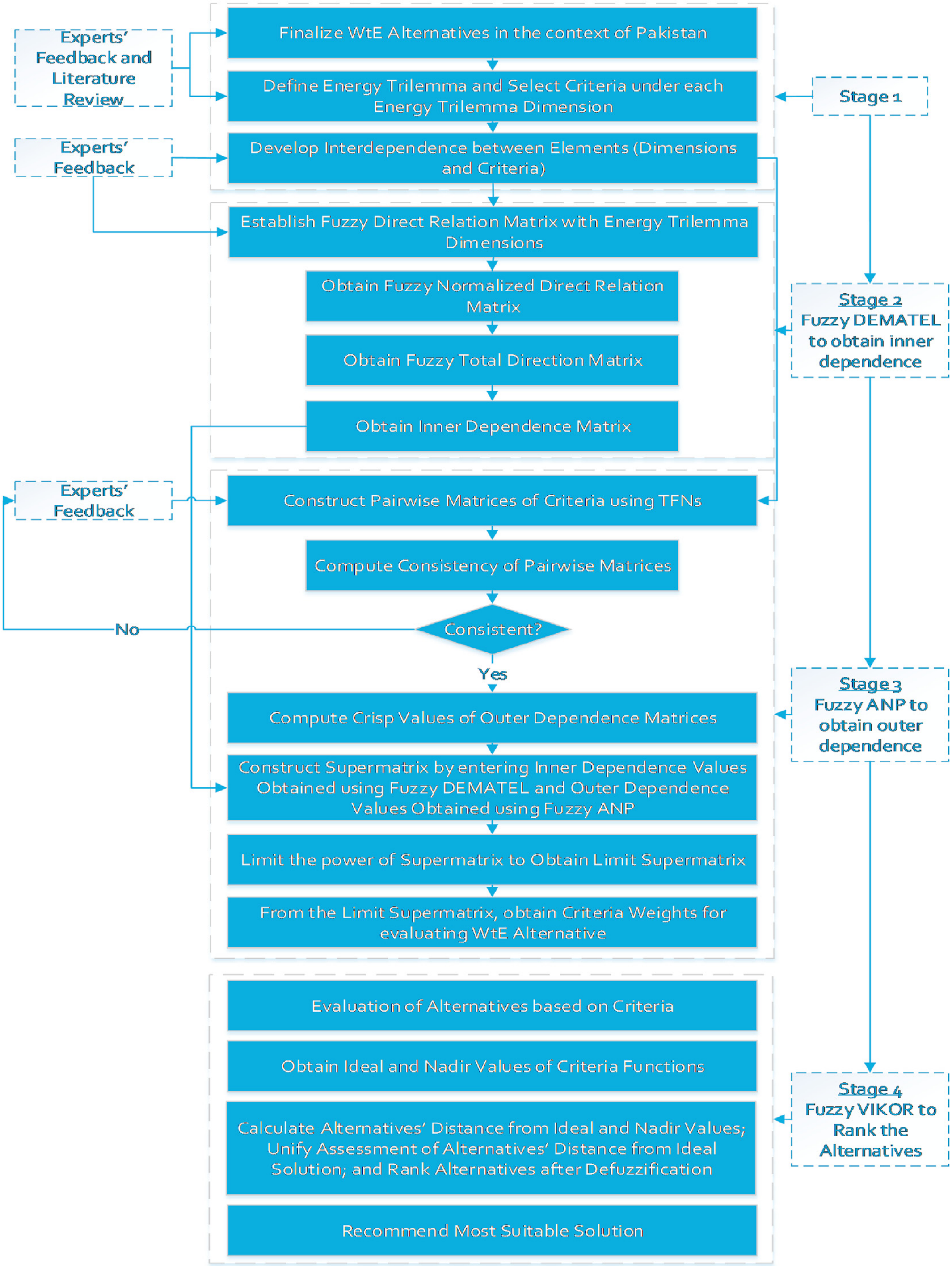

Fig. 1. Schematic of research framework.

2.1.2. *Thermo-chemical*

2.1.2.1. Torrefaction (A-2). This process converts waste into a homogenous product that is condensed via palletization to produce relatively more energy-dense product known as torrefied pellets (TOPs) or briquettes, whose properties are similar to those of coal (Batidzirai et al., 2013). TOPs are further used for thermo-chemical conversions (Yan et al., 2010). Torrefaction technology is also called mild pyrolysis because the thermo-chemical process in this technology occurs between 200 and 300 °C temperature at a low heating rate and under an inert atmosphere (Medic et al., 2010). TOPs retain about 96% of their chemical energy and are hydrophobic and unsusceptible to biodegradation. So, TOPs can be an alternate to charcoal/coal for domestic heating as well as used for co-firing power generation and gasification (Agar and Wihersaari, 2012).

2.1.2.2. Plasma technology (A-3). This technology follows physics principle related to the changing state of matter when energy is supplied to it. For instance, solid transforms into liquid, and liquid changes its state into gaseous. Based on this principle, when a gas is

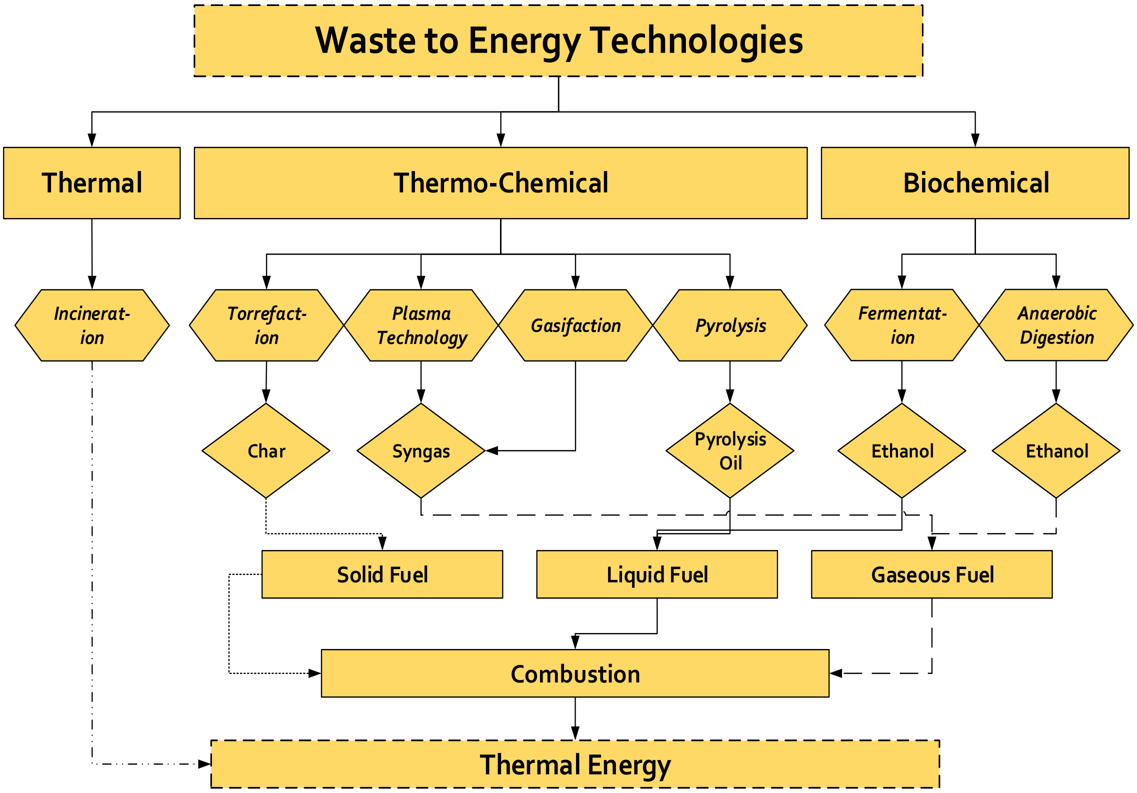

Fig. 2. Process of WtE generation technologies.

supplied with more energy, it ionizes and converts into an energy-rich plasma state that is fourth state of the matter (Nandkumar, 2014). The energy required for this reaction can either come from electric current or thermal or electromagnetic radiations. Plasma is highly reactive and behaves differently from other gases, liquids and solids due to the presence of charged gaseous species. The advantage of plasma technology is that the plasma energy enables the use of low-energy waste that would otherwise not be appropriate as feedstock for power generation through gasification technology. Nonetheless, plasma based applications for waste management are challenging as they require electricity as an initial energy vector which is costly and poses an economic barrier for using this technology (Li et al., 2016).

2.1.2.3. Gasification (A-4). This process converts waste into syngas through partial oxidation at a temperature of 600 °C or higher. Gasification happens when the char reacts with CO_2 and steam to generate hydrogen and carbon monoxide through the reaction. Besides, concentration of CO_2, steam, hydrogen, and carbon monoxide are rapidly balanced via equilibrium reaction. Among thermal WtE conversion technologies, gasification causes comparatively lower environmental pollution (Lopes et al., 2018). The obtained syngas can be used for generating heat and/or electricity. In addition to its usage in gas turbines, syngas can also produce synthetic fuels. Nonetheless, it should be noted that the production of syngas with high thermal value requires costly oxygen supply equipment (Pham et al., 2015).

2.1.2.4. Pyrolysis (A-5). Pyrolysis is the thermal decomposition of waste in an oxygen-free environment. It appears to be the most attractive option owing to its low-pollutant emission and varied products formation. The product yield of pyrolysis can be manipulated by controlling the parameters including temperature, heating rate, process time, as well as vapour residence time. There are three modes of the pyrolysis process such as, fast pyrolysis, slow pyrolysis and flash pyrolysis. The resulting product of fast pyrolysis is bio oil, slow pyrolysis is solid char and flash pyrolysis is syngas. The fast pyrolysis is usually conducted in a temperature range of 450–850 °C with short vapour residence time of 0.5–10 s and a high heating rate of 10–200 °C/s. Unlike the fast pyrolysis, the slow pyrolysis requires slow heating rate of 10–200 °C/s, and a longer vapour residence time of up to 550 s. The flash pyrolysis is carried out at extremely high heating rates that are greater than 1000 °C/s and short vapour residence time that is less than 0.5 s (Foong et al., 2020).

2.1.3. Biochemical

2.1.3.1. Fermentation (A-6). Fermentation is the process of producing ethanol that can be used further as an alternative fuel for spark-ignition engines. The ethanol produced through fermentation is considered as a biofuel since its carbon has a vegetative origin. Thus, the carbon that is emitted during the fermentation process does not increase CO_2 emissions. The process of dark fermentation is considered as most promising method. In this process, substrates are converted by anaerobic bacteria grown in the absence of light (Łukajtis et al., 2018). Despite the usefulness, fermentation has several limitations for WtE generation. For instance, the process of converting waste into bioethanol releases other types of highly polluting undesirable outputs such as distillery slope that cannot be used as bio-fertilizer or bio-slurry. Also, using bioethanol as engine fuel for electricity generation adversely affects fuel pumps by increasing undesirable spark generation and internal wear (Hassan and Kalam, 2013).

2.1.3.2. Anaerobic Digestion (A-7). This biochemical conversion process generates biogas by synthesizing waste through a series of microbial processes at about 65 °C temperature and lack of oxygen (Panepinto and Genon, 2016). Heat generation from AD can be increased by nearly 90% when methane/syngas is combusted in a cement kiln. The WtE power plants of combined heat and power can achieve an efficiency of 40%, if suitably utilized. The generated biogas can be used for heating and/or producing power. Countries with cold weather have a high demand for heat and biogas can be used to develop combined heat and/or power district heating. Besides, biogas can also be used as a fuel for vehicles after making certain changes. However, it should be noted that AD is only useful for organic waste therefore a waste separation unit is required for the process (Sailer et al., 2020).

2.2. Defining criteria based on energy trilemma

The concept of energy trilemma frequently appears in energy related discussion and literature. The notion behind the concept is to build healthy energy systems that balance between the three core dimensions such as energy security, energy equity, environmental sustainability (Song et al., 2017). Energy trilemma has pivotal role to play in post pandemic economic recovery as it emphasizes on securing an energy supply that is equitably distributed and does not afflict the environment. Fig. 3 presents three dimensions of energy trilemma and three criteria under each dimension that shall provide the basis for the evaluation of WtE alternatives in this study. These dimensions and their respective criteria are further briefly defined in the following sub-sections.

2.2.1. Energy security

Energy security is the effective management of energy supply from domestic as well as external sources (Shah et al., 2019b). Three criteria selected under this dimension are capability, resilience, and dependency, and are defined as:

Capability: It reflects the capacity of an energy system to meet the existing and future energy demands in a reliable manner.

Resilience: It displays resilience of an energy system to survive any shock and bounce back from it swiftly with minimum effect on supplies.

Dependency: Energy dependency shows how much an energy system relies on imported energy. Energy systems that mostly depend on imported energy are more vulnerable in securing energy supply amidst energy shocks or global disasters.

Those WtE alternatives that enhance capacity, strengthen resilience and reduces dependency on external energy sources shall be given preference over others with reference to improving the energy security.

2.2.2. Energy equity

Energy equity dimension emphasizes equitable access to adequate and quality energy on an affordable price for both domestic as well as commercial use (Mohsin et al., 2018). Three criteria chosen under energy equity dimension are quality, affordability, and accessibility, and are defined as:

Quality: Quality of energy encompasses access to modern and improved forms of energy that is resilient to extreme events and grid outages. It also includes modern fuels for cooking and heating that do not have negative impacts on human health.

Affordability: Provide energy access at a price that is affordable to disadvantaged and low-income communities.

Accessibility: Given the COVID-19 emergency response, access to energy has become the core need. Energy services are needed to power healthcare facilities, supply clean water for hygiene, and enable communication services that keep people connected while continuing social distancing.

Under this dimension, WtE alternatives that can increase access to quality energy services on an affordable price shall be preferred and rated higher.

2.2.3. Environmental sustainability

Environmental sustainability represents transition to low carbon and sustainable energy sources — mainly RE sources — to reduce energy led environmental harm and mitigate potential

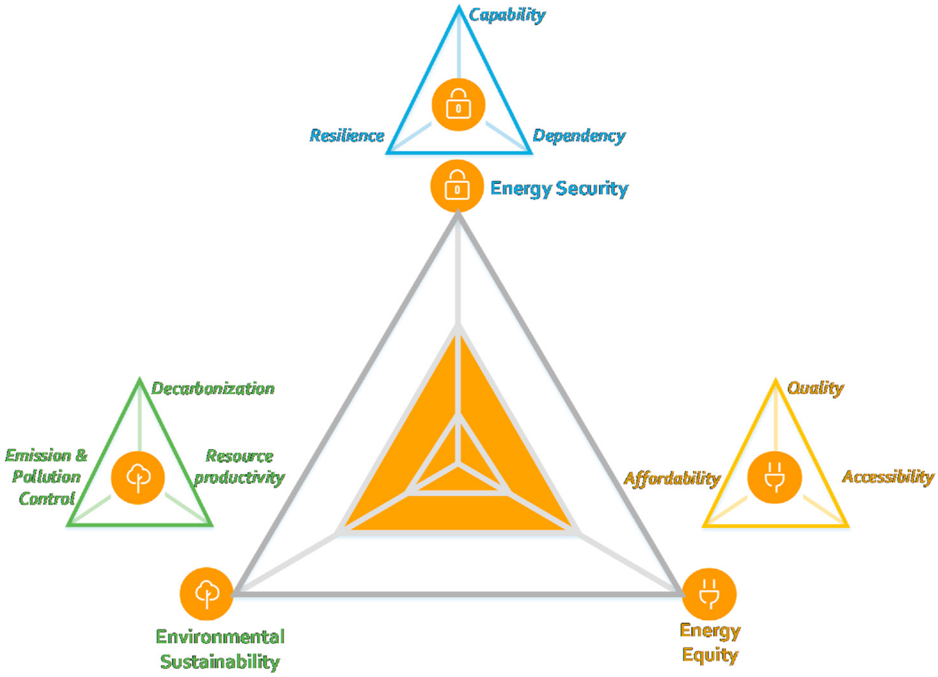

Fig. 3. Energy trilemma dimensions and sub-dimensions.

climate change impacts (Wang et al., 2018). Criteria selected under environmental sustainability dimension are decarbonisation, emission and pollution control, and resource productivity that are concisely defined as:

Decarbonisation: It refers to the minimization of carbon intensity of energy generation. Decarbonizing is the vital part of complying with the emissions reduction target submitted by the countries during the Paris agreement.

Emission and Pollution Control: It includes emissions reduction which is achieved through a corresponding decline in fossil fuels usage and an increase in the share of RE sources.

Resource Productivity: Improving resource productivity is essential to enabling the economy to grow in a lasting way out of financial crisis caused by the pandemic.

Here, WtE alternatives shall be scored as per their contribution to the criteria under environmental sustainability dimension.

2.3. *Methods*

2.3.1. *Fuzzy DEMATEL*

The Geneva Research Centre originated the DEMATEL method in the Battelle Memorial Institute. The DEMATEL method was initially aimed at the antagonistic and fragmented phenomena of the world societies and sought integrated solutions. Since its inception, the method has been widely used due to its exceptional trait of using diagraphs to portray the structure of complex causal relationship. The diagraph demonstrates the fundamental concept of contextual relationship between complex factors. While measuring a problem, the casual relationship of various criteria can be easily seen. A diagraph may typically show a dominion relationship between criteria. Although DEMATEL is prominent evaluation technique, it uses crisp numbers to establish relationship between factors in a structural model. Considering the fact that human judgement often involves uncertainty that is hard to be estimated by crisp numbers, we integrated fuzzy set theory with DEMATEL to form fuzzy DEMATEL. Similarly, there are many studies in the literature which have also preferred applying fuzzy DEMATEL. A few recent studies are quoted as: (Parmar and Desai, 2020; Feng and Ma, 2020; Xu et al., 2020; Zhang et al., 2020; Vardopoulos, 2019).

2.3.2. *Fuzzy ANP*

The ANP method is an extended form of the analytical hierarchy process (AHP) method. The benefit of using ANP over AHP is that the former works accurately in complex modeling where interrelations among various criteria is developed. The ANP method systematically evaluates all the relationships by adding potential feedbacks, interactions, and interdependences in the decision-making system. The powerful feature of this extended method is to represent a complex decision-making problem in a simple and easy way. The method does not only facilitate pairwise comparisons of criteria and sub-criteria but also enables independent comparison of interacting sub-criteria (Wu et al., 2018).

Converting a decision-making problem into a hierarchical structure is not possible in many complicated cases where higher level and lower level elements in a hierarchy are interactive and interdependent. To find out weights of elements in such circumstances, a complicated analysis would be required. The ANP method is of good use at such situations because it represents a problem by a network rather than converting it into a hierarchical structure. The feedback structure in ANP is not like top to bottom hierarchical form but seems more like a network having cycles to connect components of elements and loops to link a component to itself (Saaty, 2005).

The ANP method comprises three matrix analyses such as supermatrix, weighted supermatrix, and limit supermatrix. Supermatrix is the initial matrix that represents relative importance of all the components through pairwise comparison. As we integrate fuzzy set theory with ANP, TFNs shall be used to construct pairwise comparisons. The sum of each column of supermatrix must equal to unity so it is transformed to weighted supermatrix (Saaty, 2005). To generate relative weights, dependency relationships obtained using fuzzy DEMATEL are used. Finally, the power of supermatrix is raised to a point where weights converge and become stable. The resulting matrix is known as limit supermatrix which is solved to obtain results of decision-making problem.

2.3.3. *Fuzzy VIKOR*

VIKOR was proposed by Opricovic in 1998 with Serbian name (VlseKriterijumska Optimizacija I Kompromisno Resenje) that means multi-criteria optimization and compromise solution (Solangi et al., 2019). The purpose behind the development of this MCDM technique was to solve a decision-making problem that is discrete in nature and has conflicting and non-commensurable criteria (Opricovic and Tzeng, 2004, 2007). VIKOR is a famous MCDM method that is based on compromising solution technique (Suganthi, 2018). It is often challenging to find an alternative that simultaneously meet all the criteria, thus preference is given to a good compromising alternative. The problem gets more complicated when multiple experts with diverse opinion for alternatives are invited for decision-making. For such situations, VIKOR proves to be an effective method for prioritizing alternatives by offering maximum utility to group of decision-makers (Suganthi, 2018). This study applies fuzzy VIKOR as fuzzy logic enhances the method's ability to minimize ambiguity involved in human judgment, reasoning, preference, and perception (Wang et al., 2019).

2.4. *Computational steps of integrated methodology*

The computational steps of integrated MCDM methodology proposed for ranking WtE technologies as per the concept of energy trilemma are as follows:

Step 1. Development of evaluation model. Select WtE technology alternatives that are applicable in the context of Pakistan and define energy trilemma criteria and sub-criteria used to evaluate the alternatives. The evaluation model is presented in Fig. 4 while the alternatives and criteria have been already discussed respectively in Sections 2.1 and 2.2.

Step 2. Establish fuzzy linguistic scale. This step designs a comparison scale that shall be used to obtain experts opinion for measuring relationship among element of the structure through pairwise matrix. The scale is provided in Table 1 which has eleven linguistic terms and their TFNs for expressing diverse degrees of influence.

Step 3. Apply fuzzy DEMATEL to develop casual relations (Wu and Lee, 2007).

Step 3.1. Obtain fuzzy direct-relation matrix. Experts develop pairwise comparison matrix of criteria. Let the matrix be an $n \times n$ matrix $\widetilde{A}$, in which TFNs $\tilde{a}_{ij} = (l_{ij},\ m_{ij}, u_{ij})$ denote the effect of element i on element j.

Step 3.2. Convert fuzzy direct-relation matrix $\widetilde{A}$ into normalized fuzzy direct-relation matrix $\tilde{X}$ by applying following equation:

$$\tilde{X} = (\widetilde{A} \times s) \tag{1}$$

where $\tilde{a}_{ij} = (l_{ij},\ m_{ij}, u_{ij})$ and $s = \frac{1}{\max_{(1\le i\le n)}} \sum_{j=1}^{n} u_{ij}$.

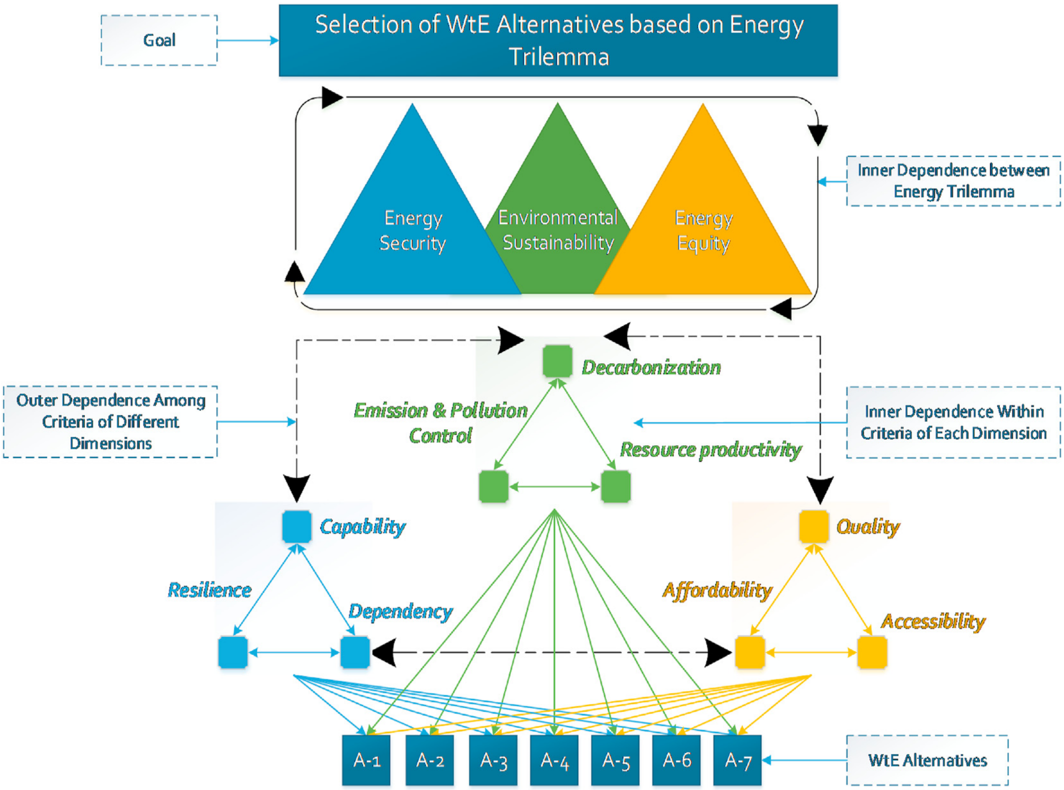

Fig. 4. Evaluation model of the decision problem.

Table 1
Fuzzy linguistic term scale.

Linguistic Term	Fuzzy Scales		
	L	m	U
None (N)	0	0	0.1
Very Low (VL)	0	0.1	0.2
Low (L)	0.1	0.2	0.3
Fairly Low (FL)	0.2	0.3	0.4
More or Less Low (ML)	0.3	0.4	0.5
Medium (M)	0.4	0.5	0.6
More or Less Good (MG)	0.5	0.6	0.7
Fairly Good (FG)	0.6	0.7	0.8
Good (G)	0.7	0.8	0.9
Very Good (VG)	0.8	0.9	1
Excellent (E)	0.9	1	1

Step 3.3. After obtaining fuzzy normalized direct-matrix, fuzzy total direct matrix $\tilde{T}$ can be obtained. To do so, we need to let the element of matrix $\tilde{X}$ denoted as $\tilde{x}_{ij} = (l_{ij},\ m_{ij}, u_{ij})$ and define three crisp matrices with their elements taken from matrix $\tilde{X}$ as follows:

$$X_l = \begin{bmatrix} 0 & l_{12} & \cdots & l_{1n} \\ l_{21} & 0 & \vdots & l_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1} & l_{n2} & \cdots & 0 \end{bmatrix}, X_m = \begin{bmatrix} 0 & m_{12} & \cdots & m_{1n} \\ m_{21} & 0 & \vdots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & 0 \end{bmatrix}, X_u = \begin{bmatrix} 0 & u_{12} & \cdots & u_{1n} \\ u_{21} & 0 & \vdots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{n1} & u_{n2} & \cdots & 0 \end{bmatrix}$$

Now we shall obtain fuzzy total direct matrix $\tilde{T}$ using the following equation as:

$$\tilde{T} = \tilde{X}(1 - \tilde{X})^{-1} \tag{2}$$

Let

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \cdots & \tilde{t}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \cdots & \tilde{t}_{nn} \end{bmatrix}$$

where $\tilde{t}_{ij} = (l'_{ij},\ m'_{ij}, u'_{ij})$ then

$$Matrix\left[l'_{ij}\right] = X_l(I - X_l)^{-1} \tag{3}$$

$$Matrix\left[m'_{ij}\right] = X_m(I - X_m)^{-1} \tag{4}$$

$$Matrix\left[u'_{ij}\right] = X_u(I - X_u)^{-1} \tag{5}$$

where I denotes identity matrix.

Step 3.4. Defuzzificate total direct matrix $\tilde{T}$ to form inner dependence matrix using below Eq. (6) (Kutlu and Ekmekçioğlu, 2012). The acquired matrix shall be used in the supermatrix of ANP.

$$P\ (a_{ij}) = \frac{l_{ij} + 4m_{ij} + u_{ij}}{6} \tag{6}$$

Step 4. Apply fuzzy ANP to develop remaining relations. Like AHP, ANP develops pairwise matrices to compare elements at each live with reference to their relative importance towards respective control criterion. Fuzzy ANP applied TFNs to draw this comparison between the pair of element for finding the relative strength of one element over another. By using pairwise comparison, a new matrix (fuzzy judgment matrix $\tilde{A}'$) is developed as:

$$\tilde{A}' = \begin{bmatrix} \tilde{a}'_{11} & \cdots & \tilde{a}'_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}'_{n1} & \cdots & \tilde{a}'_{nn} \end{bmatrix} \tag{7}$$

where $\tilde{a}'_{ij} = (l_{ij},\ m_{ij}, u_{ij})$ shows the preference of element over element, and $(i = j = 1, 2, 3, \ldots, n)$.

Step 4.1. Compute elements' relative importance weights. To complete various supermatrix submatrices, we need priority vectors for each pairwise matrix. Various methods can be used to obtain priority vectors from the matrix; we applied logarithm least-square method (Önüt et al., 2009). Let us estimate triangular fuzzy priorities $\tilde{w}_k$ as:

$$\tilde{w}_k = \left(w_k^l, w_k^m,\ w_k^u\right); \quad k = 1, 2, 3, \ldots, n$$

where

$$w_k^s = \frac{\left(\prod_{i=1}^n a_{kj}^s\right)^{1/n}}{\sum_{i=1}^n \left(\prod_{i=1}^n a_{ij}^m\right)^{1/n}}, s \in \{l, m,\ u\} \tag{8}$$

where $i = 1, 2, 3, \ldots, n$, $j = 1, 2, 3, \ldots, n$, and $0 \leq \alpha \leq 1$. To ensure results are consistent, Consistency Ratio (CR) of each matrix and overall inconsistency of hierarchy are obtained using following equation:

$$CR = \frac{CI}{RI} \tag{9}$$

where *CI* is the Consistency Index which is computed as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{10}$$

λ_{max} represents Perron root or principle eigenvalue of matrix $\tilde{A}$. *RI* is the Random Index whose values for various sizes of matrices are provided in (Saaty, 1996). For a pairwise matrix to be acceptable and consistent, it's CR should be less than 0.10.

Step 4.2. Defuzzification of weights acquired from fuzzy matrices using Eq. (6).

Step 5. Develop and solve supermatrix. The formation of a supermatrix in ANP resolves effects of interdependence among elements. The supermatrix is a segmented matrix in which submatrices are composed of quantified relations among elements from the similar or different clusters. The formation of supermatrix with three levels, goal (G), criteria (C) and alternatives (A) is as follows:

$$U = \begin{array}{c} . \\ G \\ C \\ A \end{array} \begin{array}{c} \begin{array}{ccc} G & C & A \end{array} \\ \begin{bmatrix} 0 & 0 & 0 \\ U_{21} & U_{22} & 0 \\ 0 & U_{32} & I \end{bmatrix} \end{array} \tag{11}$$

where the vector U_{21} shows the effect of goal on criteria, U_{22} shows mutual effect among criteria, U_{32} shows the effect of criteria on alternatives, and I represents the identity matrix.

To solve the supermatrix, we shall initially normalize each column by dividing weight of element in the column by the sum of weights in that column. After that, priority ranking for alternatives is obtained. To calculate overall priorities, the normalized supermatrix is raised to limited powers so that cumulative effect of each interacting element is obtained.

Step 6. Apply fuzzy VIKOR to evaluate the alternatives. The computational steps of applying fuzzy VIKOR are taken from (Opricovic, 2011) and described in following subsections.

Step 6.1. Construction of fuzzy performance matrix $\tilde{D}$ in which TFNs shall be used to evaluate alternatives with respect to criteria. The matrix $\tilde{D}$ is given as:

$$\tilde{D} = \begin{array}{c} . \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \ldots & C_n \end{array} \\ \begin{bmatrix} \tilde{f}_{11} & \ldots & \tilde{f}_{1n} \\ \vdots & \vdots & \vdots \\ \tilde{f}_{m1} & \ldots & \tilde{f}_{mn} \end{bmatrix} \end{array} \tag{12}$$

where A_k represents alternatives, $k = 1, 2, 3, \ldots, m$; C_n denotes the criterion j, $j = 1, 2, 3, \ldots, n$; and $\tilde{f}_{kj} = (l_{kj},\ m_{kj}, u_{kj})$ shows alternatives' fuzzy performance with respect to criterion.

Step 6.2. Find the ideal $\tilde{f}_j^* = (l_j^*, m_j^*,\ u_j^*)$ and the nadir $\tilde{f}_j^\circ = (l_j^\circ, m_j^\circ, u_J^\circ)$ points of criteria as per the benefit or cost functions given respectively in Equations (13) and (14) as:

$$\tilde{f}_j^* = \max_k \tilde{f}_{kj}, \ \tilde{f}_j^\circ = \min_k \tilde{f}_{kj} \quad za\, j \in j^b \tag{13}$$

$$\tilde{f}_j^* = \min_k \tilde{f}_{kj}, \ \tilde{f}_j^\circ = \max_k \tilde{f}_{kj} \quad za\, j \in j^c \tag{14}$$

Step 6.3. Calculate normalized fuzzy difference $(\tilde{d}_{kj})$ using following equation:

$$\tilde{d}_{kj} = \frac{\tilde{f}_j^* (-) \tilde{f}_{kj}}{u_J^* - l_j^\circ} \ za\, j \in \Big| j^b, \quad \tilde{d}_{kj} = \frac{\tilde{f}_{kj} (-) \tilde{f}_j^*}{u_J^\circ - l_j^*} \ za\, j \in \Big| j^c \tag{15}$$

Step 6.4. Obtain values of $\widetilde{S}_{kj} = (S_k^l,\ S_k^m,\ S_k^u)$, which denote normalized fuzzy difference such as the maximum group utility, while $\widetilde{R}_{kj} = (R_k^l, R_k^m,\ R_k^u)$ denote maximum fuzzy difference, such as minimum individual regret. These both can be calculated using following respective equations:

$$\widetilde{S}_{kj} = \sum_{j=1}^n w_j (\times) \tilde{d}_{jk} \tag{16}$$

$$\widetilde{R}_{kj} = \max_j w_j (\times) \tilde{d}_{jk} \tag{17}$$

Step 6.5. Calculate overall distances of the alternatives from the ideal solution $\widetilde{S}_{kj} = (S_k^l, S_k^m,\ S_k^u)$ using below equation:

$$\tilde{Q}_k = v \frac{\tilde{S}_k (-) \tilde{S}^*}{S^{\circ u} - S^{*l}} (+) (1 - v) \frac{\tilde{R}_k (-) \tilde{R}^*}{R^{\circ u} - R^{*l}} \tag{18}$$

where $(\tilde{S}^* = min_k \tilde{S}_k,\ S^{*l})$ is the lower value of TFN $\tilde{S}^*$, $(S^{\circ u} = max_k S_k^u)$, and $(\tilde{R}^* = min_k \tilde{R}_k,\ R^{*l})$ is the lower value of TFN $\tilde{R}^*$, $(R^{\circ u} =$

$max_k R_k^u$). The value v represents the weight of maximum group utility, and $(1 - v)$ represents the weight of individual regret.

Step 6.6. Defuzzificate $\tilde{S}_k$, $\tilde{R}_k$, and $\tilde{Q}_k$ using Eq. (6).

Step 6.7. Rank the alternatives by sorting the crisp values in ascending order. The results shall be three ranking list $\{A\}_S$, $\{A\}_R$, and $\{A\}_Q$ according to *crisp* (S), *crisp* (R), and *crisp* (Q), respectively.

Step 6.8. Obtain the compromised solution i.e. alternative $A^{(1)}$ which is ranked as best by measure Q in case if following two conditions are met:

Condition 1. "Acceptable Advantage": $Adv \geq DQ$ where $Adv = [Q(A^{(2)}) - Q(A^{(1)})]/[Q(A^{(m)}) - Q(A^{(1)})]$ is the advantage rate of alternative $A^{(1)}$ ranked first, alternative $A^{(2)}$ ranked second while $DQ = 1/(m-1)$ is the threshold.

Condition 2. "Acceptable Stability": The alternative $A^{(1)}$ must also be ranked best by S and/or R.

In case if any of these two conditions is not satisfied then the compromise solution will be obtained as below:

Compromise solution 1: Alternatives $A^{(1)}$ and $A^{(2)}$ if Condition 2 is not satisfied, or.

Compromise solution 2: Alternatives $A^{(1)}, A^{(2)}, \ldots, A^{(M)}$ is Condition 1 is not satisfied; $A^{(M)}$ is obtained by the relation $[Q(A^{(M)}) - Q(A^{(1)})]/[Q(A^{(m)}) - Q(A^{(1)})] < DQ$ for maximum M (the positions of these alternatives are in closeness.

3. Results and analysis

To evaluate WtE alternatives based on energy trilemma dimensions, computational steps given in section 2.4 are followed. Initially, structure of evaluation model is determined which is presented in Fig. 4. After defining the goal of the study, sixteen experts were invited to finalize alternatives in the context of Pakistan and to select criteria under each dimension. The experts were invited from academia, energy industry, and local municipalities. From the academia, only those experts were invited who are engaged in WtE and MSW management research and have significant related publications. The experts from industry and municipalities have vast experience of more than ten years. The objective of the study was discussed in detail with the experts who then finalized seven WtE alternatives and nine criteria (three under each dimension). Later, corresponding relationships were developed through experts' evaluation obtained using fuzzy linguistic scale given in Table 1.

Causal relationships within the energy trilemma dimensions and within criteria under each dimension were formed using fuzzy DEMATEL. For developing each causal relationship, separate fuzzy direction relation matrices were established. As an example, fuzzy direct relation matrix of energy trilemma dimensions is provided in Table 2. Later, this matrix is normalized using Eq. (4) to form normalized fuzzy direct relation matrix which is given in Table 3. The total fuzzy relation matrix is obtained from normalized fuzzy direct relation matrix using Eq. (2). Table 4 presents total fuzzy relation matrix of energy trilemma dimensions. The final step of fuzzy DEMATEL is to obtain inner dependence matrix by defuzzifying total fuzzy relation matrix using Eq. (3). The inner dependence matrix of energy trilemma dimensions is given in Table 5. The similar approach was followed to obtain inner dependence matrices of criteria under each dimension.

To establish outer dependencies between the criteria belonging to different dimensions of energy trilemma, fuzzy ANP was applied according to the procedure demonstrated in Step 4 of the integrated methodology. An example of obtaining outer dependencies between energy security criteria with respect to the energy security dimension is presented. Experts were requested to use fuzzy linguistic scale to evaluate energy security criteria (Capability, Resilience, Dependency) as per their importance to the energy security dimension. Later, Step 4.1 is applied to obtain the relative weights of criteria from fuzzy matrices. In this step, Eq. (17) and Eq. (18) were respectively applied to first solve non-linear priority and then normalize obtained values. To maintain the consistency of the results, CR for each matrix was calculated using Eq. (19). Finally, weight vectors of energy security criteria with respect to energy security dimension were obtained as; Energy Security (0.331), Energy Equity (0.332), and Environmental Sustainability (0.337). Weights of criteria under energy equity and environmental sustainability dimensions were obtained in same manner as of energy security.

The later step is to develop the supermatrix. The inner and outer dependencies values obtained respectively using fuzzy DEMATEL and fuzzy ANP shall be used as inputs in the formation of the initial supermatrix that is shown in Table A-1 in Appendix. The power of initial supermatrix shall be raised to $(2_p + 1)$ where matrix converges and thus converts into a limit supermatrix. The converged values that are given in the rows and represent criteria are normalized using $w_j' = w_j / \sum_{j=1}^{n} w_j$. The normalized values are taken as criteria weights and are shown in Fig. 5.

After obtaining the weights for criteria, the next step is to evaluate the alternatives with respect to criteria using fuzzy VIKOR and subsequently rank them. The experts were asked to score each WtE alternative with respect to all the nine criteria under three different dimensions of energy trilemma. With the help of experts' scores, fuzzy integrated preference matrixtblA2 was constructed which is given in Table A-2 in Appendix. Afterwards, ideal and nadir values of criteria are obtained using Eq. (13) and Eq. (14), respectively. Later, normalized fuzzy differences are obtained using Eq. (15). The values for maximum group utility are computed using Eq. (16), values of minimum individual regret obtained using 17, whereas the overall distance of alternatives from the ideal solution is found using Eq. (18). For the maximum group utility, weight coefficient value is used as $v = 0.5$. Finally, obtained values of maximum group utility, minimum individual regret, and overall distance are defuzzyfied using Eq. (6). Finally, three ranking lists i.e., ***Crisp***$(\boldsymbol{S})$, ***Crisp***$(\boldsymbol{R})$, and ***Crisp***$(\boldsymbol{Q})$ are formed based on defuzzyfied values. These rankings are the final results obtained using fuzzy VIKOR and are presented in Table 6.

4. Discussion

The primary objective of conducting this study is to present

Table 2
Fuzzy direct relation matrix.

	Energy Security	Energy Equity	Environmental Sustainability
Energy Security	(0, 0, 0)	(0.28, 0.37, 0.47)	(0.03, 0.1, 0.2)
Energy Equity	(0.03, 0.1, 0.2)	(0, 0, 0)	(0.02, 0.07, 0.17)
Environmental Sustainability	(0.12, 0.2, 0.3)	(0.37, 0.47, 0.57)	(0, 0, 0)

Table 3
Fuzzy normalized relation matrix.

	Energy Security	Energy Equity	Environmental Sustainability
Energy Security	(0, 0, 0)	(0.33, 0.42, 0.54)	(0.04, 0.12, 0.23)
Energy Equity	(0.04, 0.12, 0.23)	(0, 0, 0)	(0.02, 0.08, 0.19)
Environmental Sustainability	(0.13, 0.23, 0.35)	(0.42, 0.54, 0.65)	(0, 0, 0)

Table 4
Fuzzy total matrix.

	Energy Security	Energy Equity	Environmental Sustainability
Energy Security	(0.02, 0.11, 0.46)	(0.36, 0.56, 1.15)	(0.05, 0.18, 0.55)
Energy Equity	(0.04, 0.16, 0.49)	(0.02, 0.13, 0.53)	(0.02, 0.11, 0.4)
Environmental Sustainability	(0.15, 0.34, 0.83)	(0.48, 0.74, 1.39)	(0.02, 0.1, 0.46)

Table 5
Inner dependence matrix.

	Energy Security	Energy Equity	Environmental Sustainability
Energy Security	0.23	0.39	0.41
Energy Equity	0.27	0.13	0.28
Environmental Sustainability	0.51	0.49	0.31

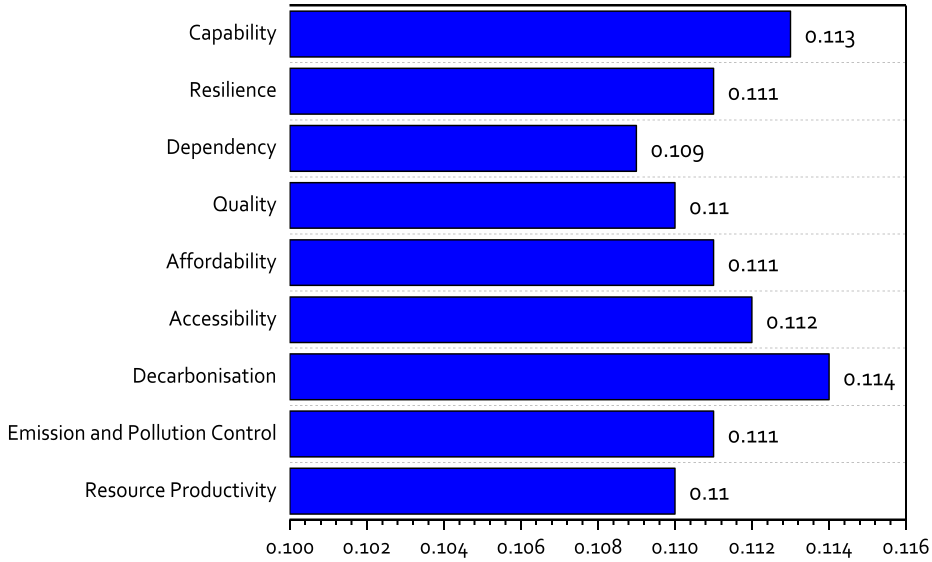

Fig. 5. Weightage of energy trilemma sub-dimensions.

Table 6
Fuzzy VIKOR results and ranking of the alternatives.

Alternatives	Crisp(S)	Rank	Crisp(R)	Rank	Crisp(Q)	Rank
Incineration (A-1)	0.3136	4	0.0538	4	0.2653	4
Torrefaction (A-2)	0.5374	7	0.0725	7	0.4052	7
Plasma Technology (A-3)	0.4958	6	0.0704	6	0.3835	6
Gasification (A-4)	0.0000	1	0.0063	1	0.0000	1
Pyrolysis (A-5)	0.1940	3	0.0428	3	0.1871	3
Fermentation (A-6)	0.3601	5	0.0587	5	0.2977	5
Anaerobic Digestion (A-7)	0.1326	2	0.0340	2	0.1369	2

optimum RE alternative for fueling the post COVID-19 economic recovery in green and sustainable way. The study is conducted in the context of Pakistan where almost every sector got severely affected by the lockdowns following a rapid surge in COVID-19 cases in the country. Subsequently, reinstating the economy becomes an urgent need for which uninterrupted and sustainable supply of energy is vital. In this study, emphasis is laid on obtaining the required energy from RE alternatives instead of relying on conventional energy sources whose usage can trigger climate catastrophes of comparatively bigger scale than the current pandemic. Also, we have observed from the recent pandemic that the world is not ready to tackle any such crisis. Therefore, wisdom lies in amending BAU pathways and adopting sustainable approaches for driving the GER.

An effort has been made in this study to guide specifically how MSW can be used to produce green energy for running the economic activities in post COVID-19 era. The study evaluates seven

WTE generation alternatives and prioritizes them based on the concept of energy trilemma. The concept of energy trilemma stresses on securing energy that is environmentally sustainable and socially equitable. Thus, the concept holds importance in fulfilling the SDG 7 that is related to ensuring universal access to energy. Each of the WtE alternative was evaluated based on three dimensions of energy trilemma (i.e., energy security, energy equity, and environmental sustainability) and nine sub-dimensions (three under each dimension). With the help of experts and literature survey, sub-dimensions were finalized under each dimension. Sub-dimensions finalized under energy security are capability, resilience, and dependency; under energy equity are quality, affordability, and accessibility; and under environmental sustainability are decarbonisation, emission and pollution control, and resource productivity.

Sixteen experts were invited to provide their feedback for the analysis. The experts came from academia, government, private energy institutes, and local municipalities. To conduct the analysis, three most dominant MCDM methods (DEMATEL, ANP, and VIKOR) along with fuzzy set theory were combined to form an integrated approach. The FDEMATEL was applied to obtain inner dependence within dimensions and sub-dimensions. Later, FANP was applied to find outer dependence among dimensions and sub-dimensions, and to compute weights of dimensions and sub-dimensions. Among dimensions, the environmental sustainability dimension obtained highest weight of 33.7% which implies that the experts stress on the necessity of decoupling environmental degradation from energy consumption and economic development in the post COVID-19 era. The energy equity dimension obtained second highest weight of 33.2% while the energy security dimension obtained 33.1%. Among the sub-dimensions, weights obtained are as follow: Decarbonisation (11.4%) > Capability (11.3%) > Accessibility (11.2%) > [Emission and Pollution Control (11.1%), Affordability (11.1%), Resilience (11.1%)] > [Resource Productivity (11.0%), Quality (11.0%)] > Dependency (10.9%).

The obtained weights for the sub-dimensions were used in the FVIKOR to rank WtE alternatives. The alternative gasification (A-4) ranked first by obtaining least score in all.

$Crisp(S)$, $Crisp(R)$, and $Crisp(Q)$. This implies that the gasification WtE alternative is the best choice for converting waste into energy that can further be used for GER in Pakistan. The second ranking is achieved by Anaerobic Digestion (A-7) by obtaining second least crisp scores. Pyrolysis (A-5) reported to obtain third ranking while Incineration (A-1) got fourth place. Fermentation (A-6) and Plasma Technology (A-3) respectively received fifth and sixth positions. Torrefaction (A-2) was placed in the bottom by obtaining maximum crisp scores. The obtained rankings were then shared with the experts who then suggested to opt for the top three alternatives keeping the gasification alternative as the first priority.

5. Conclusion and policy implications

While the impacts of the COVID-19 pandemic vary for different countries, its experience is a shared one. The economic impacts shall be lasting even after flattening the curve. The pandemic has exposed the vulnerabilities of the world. It has revealed how policy decisions taken years ago can hurt us decades later. It has shown how BAU has depleted natural world, increased social inequity, and endangered our future on the planet. Experts urge to take this pandemic as an unprecedented opportunity to shift from old fossil fuel-based economy — that led us here — and pave way toward green economy. For that, achieving SDG 7 (access to modern, affordable, equitable and sustainable energy) has become more essential than ever, not only for underpinning the response to the pandemic but also for accelerating the post-pandemic GER.

Though in the pre-pandemic era, the world was not on the track to achieve sustainable energy, now it has become even more challenging. This means that we should redouble our efforts and seek novel approaches to bring reliable, affordable and cleaner energy to all. For achieving SDG 7, implementation of energy trilemma can prove to be a game changer. The energy trilemma addresses key dimensions — energy security, energy equity, and environmental sustainability — necessary to achieve SDG 7 and build equitable, sustainable, and more resilient economies in the post-COVID-19 world. Thus, an energy trilemma based decision support framework is developed which is later used to prioritize WtE alternatives for driving economic recovery in a green and sustainable way. It is found that WtE can be a best RE alternative for providing green energy, while simultaneously limiting the carbon output and keeping the cities clean. The best WtE generation technology for Pakistan is recommended to be the gasification technology.

For accelerating the transition to RE for sustainable development after the pandemic, few key policy measures proposed for Pakistan are given below:

- Raise RE national targets and initiate stringent climate regulations.
- Safeguard current RE projects and ensure stable policy framework for establishing WtE related infrastructure.
- Secure strategic finances for WtE generation projects, invest in WtE related infrastructure, shift new investments away from fossil fuels, and make bailout conditions on environmental action.
- Scale up WtE technologies through mandates and quotas.
- Promote behavioral changes in waste management and waste segregation.
- Maintain energy access initiatives, ensure reliable and affordable electricity supply and support distributed RE solutions to fortify health, sanitation, and other vital infrastructure.
- Support workforce expansion in WtE related field, liaise with local industries and develop training to enhance knowledge and skills of local workforce.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124729.

Appendix

Table A-1
Initial Supermatrix.

	Goal	Capability	Resilience	Dependency	Quality	Affordability	Accessibility	Decarbonisation	Pollution Control	Resource Productivity	A-1	A-2	A-3	A-4	A-5	A-6	A-7
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Capability	0.18	0.34	0.13	0.15	0.2	0.61	0.26	0.08	0.06	0.46	0	0	0	0	0	0	0
Resilience	0.3	0.21	0.1	0.21	0.18	0.12	0.06	0.25	0.57	0.46	0	0	0	0	0	0	0
Dependency	0.06	0.16	0.44	0.26	0.08	0.29	0.2	0.28	0.23	0	0	0	0	0	0	0	0
Quality	0.46	0.1	0.15	0.26	0.05	0.1	0.2	0.2	0.2	0.3	0	0	0	0	0	0	0
Affordability	0.07	0.07	0.28	0.08	0.25	0.2	0.25	0.14	0.52	0.26	0	0	0	0	0	0	0
Accessibility	0.19	0.2	0.3	0.2	0.11	0.61	0.12	0.29	0.11	0.1	0	0	0	0	0	0	0
Decarbonisation	0.23	0.15	0.16	0.12	0.25	0.1	0.61	0.07	0.19	0.25	0	0	0	0	0	0	0
Pollution Control	0.09	0.26	0.26	0.21	0.1	0.2	0.12	0.13	0.59	0.23	0	0	0	0	0	0	0
Resource Productivity	0.13	0.29	0.28	0.16	0.13	0.14	0.52	0.26	0.16	0.06	0	0	0	0	0	0	0
A-1	0	0.26	0.05	0.11	0.2	0.3	0.13	0.06	0.18	0.25	1	0	0	0	0	0	0
A-2	0	0.15	0.15	0.13	0.3	0.25	0.52	0.3	0.26	0.16	0	1	0	0	0	0	0
A-3	0	0.1	0.15	0.06	0.25	0.25	0.19	0.57	0.19	0.28	0	0	1	0	0	0	0
A-4	0	0.15	0.21	0.07	0.25	0.15	0.28	0.13	0.16	0.28	0	0	0	1	0	0	0
A-5	0	0.15	0.17	0.17	0.15	0.1	0.27	0.09	0.14	0.29	0	0	0	0	1	0	0
A-6	0	0.3	0.11	0.26	0.1	0.15	0.29	0.05	0.2	0.2	0	0	0	0	0	1	0
A-7	0	0.06	0.07	0.19	0.15	0.15	0.06	0.1	0.2	0.34	0	0	0	0	0	0	1

Table A-2
Fuzzy VIKOR Integrated Matrix.

	Capability	Resilience	Dependency	Quality	Affordability	Accessibility	Decarbonisation	Emission and Pollution Control	Resource Productivity
A-1	2.125, 3.313, 4.5	2.875, 4.094, 5.313	2.625, 3.875, 5.125	4.313, 5.531, 6.75	3.563, 4.719, 5.875	4.25, 5.375, 6.5	3.375, 4.438, 5.5	3.5, 4.594, 5.688	3.125, 4.313, 5.5
A-2	1.25, 2.344, 3.438	1.438, 2.563, 3.688	1.438, 2.5, 3.563	2.5, 3.656, 4.813	2.125, 3.281, 4.438	3.625, 4.781, 5.938	2.125, 3.344, 4.563	2.375, 3.594, 4.813	2.313, 3.469, 4.625
A-3	1.5, 2.625, 3.75	2, 3.188, 4.375	2.125, 3.25, 4.375	2.875, 4.031, 5.188	2.25, 3.469, 4.688	2.25, 3.469, 4.688	2.25, 3.469, 4.688	2.625, 3.781, 4.938	2.938, 4.156, 5.375
A-4	4.063, 5.25, 6.438	5.188, 6.375, 7.563	5.188, 6.344, 7.5	5.25, 6.438, 7.625	4.563, 5.656, 6.75	5.75, 6.875, 8	6.313, 7.438, 8.563	4.688, 5.875, 7.063	4.375, 5.563, 6.75
A-5	2.5, 3.688, 4.875	3.625, 4.875, 6.125	3.875, 5.031, 6.188	4.875, 6, 7.125	4.063, 5.281, 6.5	4.813, 5.969, 7.125	3.938, 5.094, 6.25	3.875, 5.031, 6.188	3.813, 5.094, 6.375
A-6	1.625, 2.781, 3.938	2.813, 4.031, 5.25	3.125, 4.25, 5.375	3.438, 4.656, 5.875	3.125, 4.313, 5.5	4, 5.156, 6.313	3.125, 4.281, 5.438	3, 4.25, 5.5	3.25, 4.438, 5.625
A-7	2.5, 3.688, 4.875	4.188, 5.375, 6.563	3.813, 5.063, 6.313	4.75, 5.938, 7.125	4, 5.219, 6.438	5.125, 6.281, 7.438	5.5, 6.656, 7.813	4.688, 5.813, 6.938	4, 5.188, 6.375

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