More on energy and Randić energy of specific graphs

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Abstract

Let $G$ be a simple graph of order $n$. The energy $E(G)$ of the graph $G$ is the sum of the absolute values of the eigenvalues of $G$. The Randić matrix of $G$, denoted by $R(G)$, is defined as the $n \times n$ matrix whose $(i, j)$-entry is $(d_i d_j)^{-\frac{1}{2}}$ if $v_i$ and $v_j$ are adjacent and 0 for another cases. The Randić energy $RE$ of $G$ is the sum of absolute values of the eigenvalues of $R(G)$. In this paper we compute the energy and Randić energy for certain graphs. Also we propose a conjecture on Randić energy.

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1 Introduction

In this paper we are concerned with simple finite graphs, without directed, multiple, or weighted edges, and without self-loops. Let $A(G)$ be adjacency matrix of $G$ and $\lambda_1, \lambda_2, \ldots, \lambda_n$ its eigenvalues. These are said to be the eigenvalues of the graph $G$ and to form its spectrum [4]. The energy $E(G)$ of the graph $G$ is defined as the sum of the absolute values of its eigenvalues

$$E(G) = \sum_{i=1}^{n} |\lambda_i|.$$ 

Details and more information on graph energy can be found in [6,8,12].

The Randić matrix $R(G) = (r_{ij})_{n \times n}$ is defined as [2,4,9]

$$r_{ij} = \begin{cases} \frac{1}{\sqrt{d_i d_j}} & \text{if } v_i \sim v_j \\ 0 & \text{otherwise.} \end{cases}$$

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Denote the eigenvalues of the Randić matrix $R(G)$ by $\rho_1, \rho_2, \ldots, \rho_n$ and label them in non-increasing order. The Randić energy \(^{239}\) of $G$ is defined as

$$E(G) = \sum_{i=1}^{n} |\rho_i|.$$ 

Two graphs $G$ and $H$ are said to be Randić energy equivalent, or simply $\mathcal{RE}$-equivalent, written $G \sim H$, if $RE(G) = RE(H)$. It is evident that the relation $\sim$ of being $\mathcal{RE}$-equivalence is an equivalence relation on the family $\mathcal{G}$ of graphs, and thus $\mathcal{G}$ is partitioned into equivalence classes, called the $\mathcal{RE}$-equivalence classes. Given $G \in \mathcal{G}$, let

$$[G] = \{H \in \mathcal{G} : H \sim G\}.$$ 

We call $[G]$ the equivalence class determined by $G$. A graph $G$ is said to be Randić energy unique, or simply $\mathcal{RE}$-unique, if $[G] = \{G\}$.

Similarly, we can define $\mathcal{E}$-equivalence for energy and $\mathcal{E}$-unique for a graph.

A graph $G$ is called $k$-regular if all vertices have the same degree $k$. One of the famous graphs is the Petersen graph which is a symmetric non-planar 3-regular graph. In the study of energy and Randić energy, it is interesting to investigate the characteristic polynomial and energy of this graph. We denote the Petersen graph by $P$.

In this paper, we study the energy and Randić energy of specific graphs. In the next section, we study energy and Randić energy of 2-regular and 3-regular graphs. We study cubic graphs of order 10 and list all characteristic polynomial, energy and Randić energy of them. As a result, we show that Petersen graph is not $\mathcal{RE}$-unique ($\mathcal{E}$-unique) but can be determined by its Randić energy (energy) and its eigenvalues. In the last section we consider some another families of graphs and study their Randić characteristic polynomials.

## 2 Energy of 2-regular and 3-regular graphs

The energy and Randić energy of regular graphs have not been widely studied. In this section we consider 2-regular and 3-regular graphs. The following theorem gives a relationship between the Randić energy and energy of $k$-regular graphs.
Lemma 1 \[\text{[10]}\] If the graph $G$ is $k$-regular then $RE(G) = \frac{1}{k}E(G)$.

Also we have the following easy lemma:

**Lemma 2.** Let $G = G_1 \cup G_2 \cup \ldots \cup G_m$. Then

(i) $E(G) = E(G_1) + E(G_2) + \ldots + E(G_m)$.

(ii) $RE(G) = RE(G_1) + RE(G_2) + \ldots + RE(G_m)$.

\[\text{Randić characteristic polynomial of the cycle graph } C_n \text{ can be determined by the following theorem:}\]

**Lemma 3** \[\text{[1]}\] For $n \geq 3$, the Randić characteristic polynomial of the cycle graph $C_n$ is

$$RP(C_n, \lambda) = \lambda \Lambda_{n-1} - \frac{1}{2} \Lambda_{n-2} - \left(\frac{1}{2}\right)^{n-1},$$

where for every $k \geq 3$, $\Lambda_k = \lambda \Lambda_{k-1} - \frac{1}{4} \Lambda_{k-2}$ with $\Lambda_1 = \lambda$ and $\Lambda_2 = \lambda^2 - \frac{1}{4}$.

By Lemma 3 we can find all the eigenvalues of Randić matrix of cycle graphs. So we can compute the Randić energy of cycles. Also every cycle is 2-regular. By Lemma 1 we have $E(C_n) = 2RE(C_n)$. Hence we can compute energy of cycle graphs too. Every 2-regular graph is a disjoint union of cycles. Therefore by Lemma 2 we can find energy and Randić energy of 2-regular graphs.

Let to consider the characteristic polynomial of 3-regular graphs of order 10. Also we shall compute energy and Randić energy of this class of graphs. There are exactly 21 cubic graphs of order 10 given in Figure 1 (see \[\text{[1]}\](11)).

We show that Petersen graph is not $\mathcal{RE}$-unique ($\mathcal{E}$-unique) but can be determined by its Randić energy (energy) and its eigenvalues. There are just two non-connected cubic graphs of order 10. The following theorem gives us characteristic polynomial of 3-regular graphs of order 10. We denote the characteristic polynomial of the graph $G$ by $P(G, \lambda)$. 
Using Maple we computed the characteristic polynomials of 3-regular graphs of order 10 in Table 1.
By computing the roots of characteristic polynomial of cubic graphs of order 10, we can have the energy of these graphs. We compute them to four decimal places. So we have table 2:

| $G_i$ | $E(G_i)$ | $RE(G_i)$ | $G_i$ | $E(G_i)$ | $RE(G_i)$ | $G_i$ | $E(G_i)$ | $RE(G_i)$ |
|-------|----------|------------|-------|----------|------------|-------|----------|------------|
| $G_1$ | 15.1231  | 5.0410     | $G_8$ | 15.1231  | 5.0410     | $G_{15}$ | 14.7943  | 4.9314     |
| $G_2$ | 14.8596  | 4.9532     | $G_9$ | 15.3164  | 5.1054     | $G_{16}$ | 14.0000  | 4.6666     |
| $G_3$ | 14.8212  | 4.9404     | $G_{10}$ | 14.4721  | 4.8240     | $G_{17}$ | 16.0000  | 5.3333     |
| $G_4$ | 13.5143  | 4.5047     | $G_{11}$ | 14.7020  | 4.9006     | $G_{18}$ | 13.5569  | 4.5189     |
| $G_5$ | 14.2925  | 4.7641     | $G_{12}$ | 16.0000  | 5.3333     | $G_{19}$ | 15.5791  | 5.1930     |
| $G_6$ | 14.9443  | 4.9814     | $G_{13}$ | 14.3780  | 4.7926     | $G_{20}$ | 14.0000  | 4.6666     |
| $G_7$ | 15.0777  | 5.0259     | $G_{14}$ | 15.0895  | 5.0298     | $G_{21}$ | 12.0000  | 4.0000     |

Table 2. Energy and Randić energy of cubic graphs of order 10.
**Theorem 1.** Six cubic graphs of order 10 are not $\mathcal{E}$-unique ($\mathcal{RE}$-unique). If two cubic graphs of order 10 have equal energy (Randić energy), then their eigenvalues are different in exactly 3 values.

**Proof.** Using Table 2, we see that $[G_1] = \{G_1, G_8\}$, $[G_{12}] = \{G_{12}, G_{17}\}$ and $[G_{16}] = \{G_{16}, G_{20}\}$. Now, it suffices to find the eigenvalues of $G_1, G_8, G_{12}, G_{16}$, $G_{17}$ and $G_{20}$. By Table 1 we have:

\[
P(G_1, \lambda) = \lambda^{10} - 15\lambda^8 - 8\lambda^7 + 71\lambda^6 + 64\lambda^5 - 101\lambda^4 - 104\lambda^3 + 44\lambda^2 + 48\lambda
\]

\[
= \lambda(\lambda - 3)(\lambda + 2)^2(\lambda - 1)^2(\lambda + 1)^2(\lambda - \frac{1 - \sqrt{17}}{2})(\lambda - \frac{1 + \sqrt{17}}{2}),
\]

\[
P(G_8, \lambda) = \lambda^{10} - 15\lambda^8 + 71\lambda^6 - 16\lambda^5 - 133\lambda^4 + 64\lambda^3 + 76\lambda^2 - 48\lambda
\]

\[
= \lambda(\lambda - 3)(\lambda + 2)^2(\lambda - 1)^3(\lambda + 1)(\lambda - \frac{-1 + \sqrt{17}}{2})(\lambda - \frac{-1 - \sqrt{17}}{2}),
\]

Also

\[
P(G_{12}, \lambda) = \lambda^{10} - 15\lambda^8 - 4\lambda^7 + 75\lambda^6 + 24\lambda^5 - 157\lambda^4 - 36\lambda^3 + 144\lambda^2 + 16\lambda - 48
\]

\[
= (\lambda - 3)(\lambda - 2)(\lambda + 2)^3(\lambda - 1)^3(\lambda + 1)^2,
\]

\[
P(G_{17}, \lambda) = \lambda^{10} - 15\lambda^8 + 75\lambda^6 - 24\lambda^5 - 165\lambda^4 + 120\lambda^3 + 120\lambda^2 - 160\lambda + 48
\]

\[
= (\lambda - 3)(\lambda + 2)^4(\lambda - 1)^5.
\]

And

\[
P(G_{16}, \lambda) = \lambda^{10} - 15\lambda^8 + 63\lambda^6 - 85\lambda^4 + 36\lambda^2
\]

\[
= \lambda^2(\lambda - 3)(\lambda + 3)(\lambda - 2)(\lambda + 2)(\lambda - 1)^2(\lambda + 1)^2,
\]

\[
P(G_{20}, \lambda) = \lambda^{10} - 15\lambda^8 - 12\lambda^7 + 63\lambda^6 + 96\lambda^5 - 13\lambda^4 - 84\lambda^3 - 36\lambda^2
\]

\[
= \lambda^2(\lambda - 3)^2(\lambda + 2)^2(\lambda - 1)(\lambda + 1)^3.
\]

So we have the result. \(\square\)

Now we consider Petersen graph $P$. We have shown this graph in Figure.
Theorem 2. Let $\mathcal{G}$ be the family of 3-regular graphs of order 10. For the Petersen graph $P$, we have the following properties:

(i) $P$ is not $\mathcal{E}$-unique ($\mathcal{RE}$-unique) in $\mathcal{G}$.

(ii) $P$ has the maximum energy (Randić energy) in $\mathcal{G}$.

(iii) $P$ can be identify by its energy (Randić energy) and its eigenvalues in $\mathcal{G}$.

Proof.

(i) The adjacency matrix of $P$ is

$$A(P) = \begin{pmatrix}
0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0
\end{pmatrix}.$$  

So $\det(\lambda I - A(P)) = (\lambda - 3)(\lambda + 2)^4(\lambda - 1)^5$. Therefore we have:

$$\lambda_1 = 3 \ , \ \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = -2 \ , \ \lambda_6 = \lambda_7 = \lambda_8 = \lambda_9 = \lambda_{10} = 1,$$
and so we have $E(P) = 16$. By Table 2, we have $P \in \{G_{12}, G_{17}\}$. Hence $P$ is not $\mathcal{E}$-unique (and $\mathcal{RE}$-unique) in $\mathcal{G}$.

(ii) It follows from Part (i) and Table 2.

(iii) It follows from Part (i) and Theorem 1. So $G_{17}$ is the Petersen graph.

The following result gives a relationship between energy and permanent of adjacency matrix of two connected graphs in the family of cubic graphs of order 10 whose have the same $\mathcal{E}$-equivalence class.

**Theorem 3.** If two connected cubic graphs of order 10 have the same energy, then their adjacency matrices have the same permanent.

**Proof.** By Table 2, it suffices to find $\text{per}(A(G_1))$, $\text{per}(A(G_8))$, $\text{per}(A(G_{12}))$ and $\text{per}(A(G_{17}))$.

For graph $G_1$, we have

$$A(G_1) = \begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\
1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0
\end{pmatrix}.$$  

By Ryser’s method, we have $\text{per}(A(G_1)) = 72$. Similarly we have:

$$\text{per}(A(G_8)) = 72 \ , \ \text{per}(A(G_{12})) = 60 \ , \ \text{per}(A(G_{17})) = 60.$$  

So we have the result.

**Remark 1.** The converse of Theorem 3 is not true. Because $\text{per}(A(G_7)) = \text{per}(A(G_{11})) = 85$, but as we see in Table 2, $E(G_7) \neq E(G_{11})$. 


Corollary 1. If two connected cubic graphs of order 10 have the same Randić energy, then their adjacency matrices have the same permanent.

Proof. It follows from Lemma 1, Table 2 and Theorem 3.

3 Randić characteristic polynomial of a kind of Dutch-Windmill graphs

We recall that a complex number \( \zeta \) is called an algebraic number (resp. an algebraic integer) if it is a root of some monic polynomial with rational (resp. integer) coefficients (see [13]). Since the Randić characteristic polynomial \( P(G, \lambda) \) is a monic polynomial in \( \lambda \) with integer coefficients, its roots are, by definition, algebraic integers. This naturally raises the question: Which algebraic integers can occur as zeros of Randić characteristic polynomials? And which real numbers can occur as Randić energy of graphs? We are interested to numbers which are occur as Randić energy. Clearly those lying in \((-\infty, 2)\) are forbidden set, because we know that if graph \( G \) possesses at least one edge, then \( RE(G) \geq 2 \). We think that the Randić energy of graphs are dense in \([2, \infty)\). In this section we would like to study some further results of this kind.

Let \( n \) be any positive integer and \( D^n_m \) be Dutch Windmill graph with \((m - 1)n + 1\) vertices and \( mn \) edges. In other words, the graph \( D^n_m \) is a graph that can be constructed by coalescence \( n \) copies of the cycle graph \( C_m \) of length \( m \) with a common vertex. We recall that \( D^3_3 \) is friendship graphs. Figure 3 shows some examples of this kind of Dutch Windmill graphs. In this section we shall investigate the Randić characteristic polynomial of Dutch Windmill graphs.

By Lemma 3 we know that

\[
RP(C_m, \lambda) = \lambda \Lambda_{m-1} - \frac{1}{2} \Lambda_{m-2} - \left(\frac{1}{2}\right)^{m-1},
\]

where for every \( k \geq 3 \), \( \Lambda_k = \lambda \Lambda_{k-1} - \frac{1}{4} \Lambda_{k-2} \) with \( \Lambda_1 = \lambda \) and \( \Lambda_2 = \lambda^2 - \frac{1}{4} \). We show that the Randić characteristic polynomial of Dutch Windmill graphs can compute by the cycle which constructed it.
Figure 3: Dutch Windmill Graph $D_4^2, D_4^3, D_4^4$ and $D_4^n$, respectively.

**Theorem 4.** For $m \geq 3$, the Randić characteristic polynomial of the Dutch Windmill graph $D_m^n$ is

$$RP(D_m^n, \lambda) = \Lambda_{m-1}^{n-1}RP(C_m, \lambda),$$

where for every $k \geq 3$, $\Lambda_k = \lambda \Lambda_{k-1} - \frac{1}{4} \Lambda_{k-2}$ with $\Lambda_1 = \lambda$ and $\Lambda_2 = \lambda^2 - \frac{1}{4}$.

**Proof.** For every $k \geq 3$, consider

$$B_k := \begin{pmatrix} \lambda & -\frac{1}{2} & 0 & 0 & \ldots & 0 & 0 & 0 \\ -\frac{1}{2} & \lambda & -\frac{1}{2} & 0 & \ldots & 0 & 0 & 0 \\ 0 & -\frac{1}{2} & \lambda & -\frac{1}{2} & \ldots & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{2} & \lambda & \ldots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \ldots & \lambda & -\frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & \ldots & -\frac{1}{2} & \lambda & -\frac{1}{2} \\ 0 & 0 & 0 & 0 & \ldots & 0 & -\frac{1}{2} & \lambda \end{pmatrix}_{k \times k}$$

and let $\Lambda_k = det(B_k)$. It is easy to see that $\Lambda_k = \lambda \Lambda_{k-1} - \frac{1}{4} \Lambda_{k-2}$.

Suppose that $RP((D_m^n, \lambda) = det(\lambda I - R((D_m^n))$. We have
\[ RP((D^n_m, \lambda)) = \det \begin{pmatrix} \lambda & A & A & \ldots & A \\ A^t & B_{m-1} & 0 & \ldots & 0 \\ A^t & 0 & B_{m-1} & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^t & 0 & 0 & \ldots & B_{m-1} \end{pmatrix}, \]

where \( A = \left( \begin{array}{cccc} -\frac{1}{2\sqrt{n}} & 0 & 0 & \ldots & 0 \\ \end{array} \right)_{1 \times (m-1)} \). So

\[ \det(\lambda I - R((D^n_m))) = \lambda \Lambda_{m-1}^n + \left( -\frac{1}{4} \Lambda_{m-2} + 2((-1)^{m+1}(-\frac{1}{2})^m) + (-1)^{2m+1}(-\frac{1}{4}) \Lambda_{m-2} \right) \Lambda_{m-1}^{n-1}. \]

Therefore

\[ \det(\lambda I - R((D^n_m))) = \lambda \Lambda_{m-1}^n + \left( -\frac{1}{2} \Lambda_{m-2} - (\frac{1}{2})^{m-1} \right) \Lambda_{m-1}^{n-1}. \]

Hence

\[ \det(\lambda I - R((D^n_m))) = \Lambda_{m-1}^{n-1} \left( \lambda \Lambda_{m-1} - \frac{1}{2} \Lambda_{m-2} - (\frac{1}{2})^{m-1} \right) = \Lambda_{m-1}^{n-1} RP(C_m, \lambda). \]

In [1] we have presented two families of graphs such that their Randić energy are \( n + 1 \) and \( 2 + (n - 1)\sqrt{2} \). Here we recall the following results:

**Theorem 5.** [1]

(i) The Randić energy of friendship graph \( F_n \) is \( RE(F_n) = n + 1 \).

(ii) The Randić energy of Dutch-Windmill graph \( D^n_4 \) is \( RE(D^n_4) = 2 + (n - 1)\sqrt{2} \).

(iii) For every \( m, n \geq 2 \), the Randić energy of \( K_{m,n} - e \) is \( RE(K_{m,n} - e) = 2 + \frac{2}{\sqrt{mn}} \).

We can use Theorem 4 to obtain \( RE(D^n_5) \). Here using the definition of Randić characteristic polynomial, we prove the following result:
Theorem 6. The Randić energy of $D_5^n$ is

$$RE(D_5^n) = 1 + n\sqrt{5}.$$  

Proof. The Randić matrix of $D_5^n$ is

$$R(D_5^n) = \begin{pmatrix} 0 & \frac{1}{2\sqrt{n}} & \frac{1}{2\sqrt{n}} & 0 & 0 & \cdots & \frac{1}{2\sqrt{n}} & \frac{1}{2\sqrt{n}} & 0 & 0 \\ \frac{1}{2\sqrt{n}} & 0 & 0 & \frac{1}{2} & 0 & \cdots & 0 & 0 & 0 & 0 \\ \frac{1}{2\sqrt{n}} & 0 & 0 & 0 & \frac{1}{2} & \cdots & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \frac{1}{2\sqrt{n}} & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \frac{1}{2} & 0 \\ \frac{1}{2\sqrt{n}} & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 & 0 & 0 & \cdots & \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \frac{1}{2} & 0 & \frac{1}{2} \end{pmatrix}.$$  

Let $A = \begin{pmatrix} \lambda & 0 & -\frac{1}{2} & 0 \\ 0 & \lambda & 0 & -\frac{1}{2} \\ -\frac{1}{2} & 0 & \lambda & -\frac{1}{2} \\ 0 & -\frac{1}{2} & -\frac{1}{2} & \lambda \end{pmatrix}$ and $C = \begin{pmatrix} -\frac{1}{2\sqrt{n}} & 0 & -\frac{1}{2} & 0 \\ 0 & -\frac{1}{2\sqrt{n}} & 0 & -\frac{1}{2} \\ -\frac{1}{2} & 0 & \lambda & -\frac{1}{2} \\ 0 & -\frac{1}{2} & -\frac{1}{2} & \lambda \end{pmatrix}.$ Then

$$\det(\lambda I - R((D_5^n))) = \lambda \det(A)^n + \sqrt{n} \det(C) \det(A)^{n-1}.$$  

So

$$\det(\lambda I - R((D_5^n))) = \det(A)^{n-1}(\lambda - 1)(\lambda - (\frac{\sqrt{5}}{4} - \frac{1}{4}))^2(\lambda + (\frac{\sqrt{5}}{4} + \frac{1}{4}))^2.$$  

Hence

$$RE(D_5^n) = 1 + n\sqrt{5}. \quad \Box$$
Part (iii) of Theorem 5 implies that the Randić energy of graphs are dense in $[2, 3)$. Motivated by this notation, Theorems 5 and 6, we think that the Randić energy of graphs are dense in $[2, \infty)$. We close this paper by the following conjecture:

**Conjecture 1.** Randić energy of graphs are dense in $[2, \infty)$. 

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