European electricity network: analysis on electricity exchanges and decarbonization scenarios in the European power grid.

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1 Introduction

This project analyzes the electricity trades between European states and evaluates the carbon density of the electric generation system with networks.

The work is divided into two parts. In the first part, real data is used to construct the networks. A comparison is made between the network built using data from the years before COVID-19 (2017-2019) and the network built using data from the COVID-19 period (2020). This evaluation aims to assess the perturbations in the European electric system (electricity production, carbon density, and other network properties) caused by the virus.

I used this data also to analyze the current interdependencies between states through a reinterpretation of the HITS algorithm.

In the second part of the project, a simulation is conducted to reconstruct and reorganize the electricity mix of the European states by eliminating the most polluting sources (coal, oil, gas). The goal is to achieve a clean energy transition in 2050.

In the simulation, certain assumptions and approximations were made regarding the future energy consumption of Europe and what would constitute an acceptable energy mix for the countries. These hypotheses and approximations will be thoroughly explained in the subsequent sections.

2 How to run the code

Code is written in python, you can execute the codes in the following way:

```
python3 FileName.py
```

To successfully run the code, the following libraries are required:

- pandas
- numpy
- networkx
- matplotlib

you can install them using pip:

```
pip install networkx
```

if you don't have pip you can install them with the following command line:

```
sudo apt-get install pip
```

3 Networks of the current electric grid

The networks I have built have different features. The dimensions of the nodes are proportional to the amount of electricity produced by each state. The color of the nodes represents the carbon density of energy production in each state, while the width of the links represents the quantity of electric power that passes through the nodes.

I used different datasets to create these networks. In the "DataSets" folder of the repository, you can find the raw files I worked on: "Flow_graph_2017-19.txt" and "Flow_graph_2020.txt" contain the data on power flows between states, which were used to create the links of the networks [1]. The file "Electricity_Production_TWh.txt" contains the energy production of each state (in TWh), which I used to set the dimensions of the nodes [2]. The file "share-elec-produc-by-source.txt" provides the contribution of each type of electricity generation for each state, which I used to calculate the carbon density [3]. I applied six different colorations: green for a production level below 100 gCO2/kWh, light green for a production level between 100-200 gCO2/kWh, yellow for a production level between 200-300 gCO2/kWh, orange for a production level between 300-400 gCO2/kWh, red for a production level between 400-500 gCO2/kWh, and brown for a production level above 600 gCO2/kWh. The carbon intensity of each source of energy is taken from IPCC [4].

The "DataSet" folder contains only raw and processed files that can be ignored for code execution. The relevant files are all located in the main directory.

3.1 Influence of the COVID-19 on the European electricity grid

By executing the "2017-19.py" and "2020.py" scripts, we can obtain the first two networks of the project. These are weighted directed networks where the links are created by calculating the total balance, which is determined by the difference in electricity flowing through two nodes in both directions.

The first script creates a network using data from the first week of 2017 to the last week of 2019, taking the mean values (1). The second script uses data from all weeks of 2020 to create another network (2).

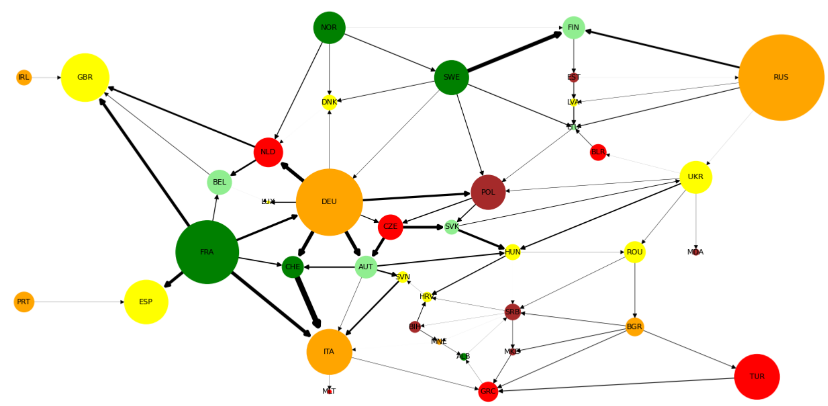

Figure 1: Network of the European electricity grid in the years 2017-2019, for a better visualization run the code.

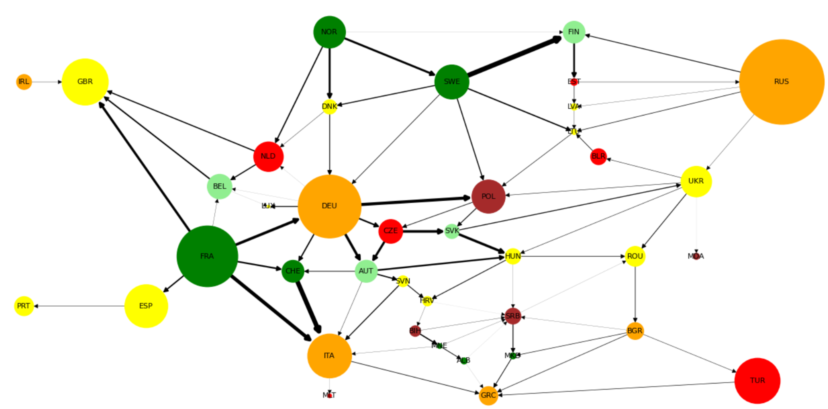

Figure 2: Network of the European electricity grid in the year 2020, for a better visualization run the code.

In the first network we have a total production 5025.3 TWh of energy and a carbon density of 313.8 gCO2/kWh, in the second network (year of the COVID-19) we have a total production of 4830.7 TWh and a carbon density of 279.3 gCO2/kWh, so we can see a reduction of the total production of energy of 3.9% and a carbon density is diminished of 11.0%.

In the first network, representing the years 2017-2019, the total production of energy is 5025.3 TWh, and the carbon density is 313.8 gCO2/kWh. In the second network, representing the year of the COVID-19 pandemic, the total production of energy is 4830.7 TWh, and the carbon density is 279.3 gCO2/kWh. This indicates a reduction in total energy production by 3.9% and a decrease in carbon density by 11.0%.

These observations suggest that during the year of the COVID-19 pandemic, there was a decrease in energy production and a reduction in carbon intensity, possibly due to changes in energy consumption patterns, economic activity, and environmental policies implemented during that period. We can observe a relatively big reduction in carbon density also because the two source of energy that can be easily modulated and programmable are coal and gas, which are known for their high carbon emissions.

3.2 HITS algorithm

From the previous networks has been calculated the HITS algorithm that it's implemented on the library of NetworkX [5].

Hyperlink-Induced Topic Search (HITS; also known as hubs and authorities) is a link analysis algorithm that rates Web pages, a good hub represents a page that pointed to many other pages, while a good authority represents a page that is linked by many different hubs. The scheme assigns two scores for each page: its authority, which estimates the value of the content of the page, and its hub value, which estimates the value of its links to other pages.

Within this project, I have reinterpreted the meaning of the HITS algorithm. Nodes with a high value of hubs indicate nodes that have a surplus of electricity production, enabling them to export energy to neighboring nodes. Instead, nodes with a high value of authorities represent nodes with a deficit of electricity production, making them highly dependent on other nodes for their energy supply.

The values of hits algorithm are in tables (1) (2).

	Hubs			Authorities
FRA	0.326		ITA	0.307
CHE	0.272		GBR	0.113
DEU	0.154		ESP	0.110
SVN	0.076		CHE	0.108
AUT	0.042		DEU	0.081
NLD	0.042		AUT	0.071
CZE	0.037		NLD	0.061
SWE	0.013		POL	0.039
NOR	0.009		BEL	0.038
BEL	0.009		CZE	0.016
POL	0.004		LUX	0.016
UKR	0.003		SVK	0.011
PRT	0.003		HUN	0.007
SVK	0.003		DNK	0.007
IRL	0.002		FIN	0.006
RUS	0.002		SVN	0.006
LTU	0.002		LTU	0.001
LVA	0.000		SWE	0.001
MNE	0.000		UKR	0.000
BLR	0.000		ROU	0.000
HRV	0.000		MDA	0.000
DNK	0.000		LVA	0.000
EST	0.000		BLR	0.000
HUN	0.000		ALB	0.000
GRC	0.000		HRV	0.000
BIH	0.000		RUS	0.000
SRB	0.000		MNE	0.000
BGR	0.000		SRB	0.000
ROU	0.000		MKD	0.000
ALB	0.000		BIH	0.000
TUR	0.000		GRC	0.000
MKD	0.000		TUR	0.000
ITA	0.000		BGR	0.000
FIN	0.000		IRL	0.000
ESP	0.000		MLT	0.000
GBR	0.000		FRA	0.000
LUX	0.000		EST	0.000
MDA	0.000		PRT	0.000
MLT	0.000		NOR	0.000

Table 1: Values of hubs and authorities of the nodes for the years before the COVID-19 (2017-2019).

	Hubs			Authorities
FRA	0.393		ITA	0.386
CHE	0.292		DEU	0.153
SVN	0.061		GBR	0.140
SWE	0.048		CHE	0.094
DEU	0.043		ESP	0.073
AUT	0.034		FIN	0.032
BEL	0.032		POL	0.025
NLD	0.029		AUT	0.018
DNK	0.022		BEL	0.016
MNE	0.01		CZE	0.010
CZE	0.008		HUN	0.009
IRL	0.006		LTU	0.009
NOR	0.005		DNK	0.008
RUS	0.005		HRV	0.007
SVK	0.004		LUX	0.006
UKR	0.002		SVN	0.006
LTU	0.002		SVK	0.003
POL	0.001		NLD	0.002
HUN	0.001		SWE	0.001
BLR	0.001		ALB	0.001
LVA	0.000		UKR	0.001
EST	0.000		ROU	0.000
BIH	0.000		SRB	0.000
BGR	0.000		LVA	0.000
SRB	0.000		BLR	0.000
ALB	0.000		MDA	0.000
HRV	0.000		MNE	0.000
MKD	0.000		MKD	0.000
ITA	0.000		RUS	0.000
TUR	0.000		GRC	0.000
ROU	0.000		TUR	0.000
GBR	0.000		BIH	0.000
GRC	0.000		MLT	0.000
LUX	0.000		IRL	.000
MDA	0.000		BGR	0.000
MLT	0.000		FRA	0.000
PRT	0.000		PRT	0.000
ESP	0.000		EST	0.000
FIN	0.000		NOR	0.000

Table 2: Values of hubs and authorities of the nodes on the year of the COVID-19 (2020).

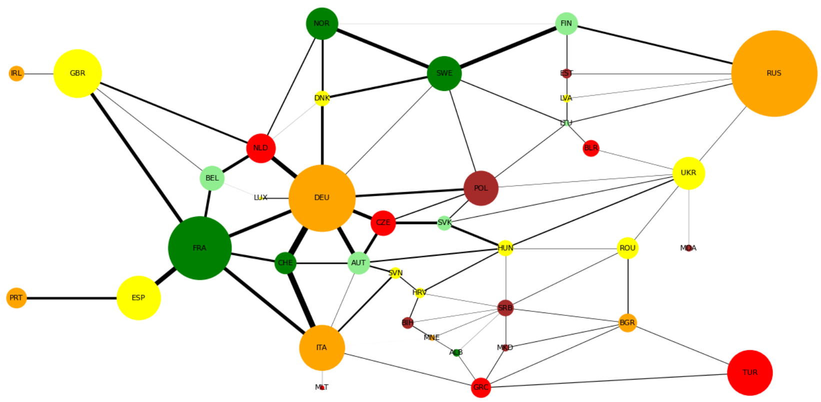

Figure 3: Weighted undirected network of the European electric grid that represent all the flow through the nodes (for a better visualization run the code).

3.3 centrality measures

With this project we can determine also some centralities measures running the file "unweighted_2017-19.py", thanks to this code we can obtain a new weighted undirected graph in which links are created with the sum of the electricty flows that passes through the nodes in both directions (fig. 3). I used the same dataset of "2017-19.py" file.

The centralities that have been calculated are four: current flow betweennes centrality (CFBC on table 3), edge current flow betweennes centrality, current flow closeness centralities (CFCC on table 3), laplacian centralities (LC on table 3).

The current flow betweenness centrality (computed thanks to corresponding NetworkX function [6]) is calculated by measuring the amount of current that passes through that node when electrical current is injected at all possible source nodes and extracted at all possible sink nodes in the network. The more current that flows through a node, the higher its current flow betweenness centrality [7].

The edge current flow betweenness centrality (computed thanks to corresponding NetworkX function [8]) has the same aim of the current flow betweenness centrality but for the edges.

The current flow closeness (computed thanks to corresponding NetworkX function [9]) centrality is variant of closeness centrality based on effective resistance between nodes in a network. This metric is also known as information centrality [10].

The Laplacian centralities (computed thanks to corresponding NetworkX function [11]) provides insights into the overall influence or significance of nodes in a network, nodes with high Laplacian centrality are those that are well-connected to other nodes and have a high influence within the network. They represent key positions that bridge different parts of the network or act as connectors between communities [12].

	CFBC			CFCC			LC
DEU	0.451		DEU	12431.9		DEU	0.483
FRA	0.281		CHE	11862.3		FRA	0.295
ITA	0.268		AUT	11808.6		CHE	0.288
SWE	0.238		FRA	11778.1		AUT	0.170
HUN	0.234		ITA	11652.6		ITA	0.167
AUT	0.191		CZE	11498.8		NLD	0.144
UKR	0.187		NLD	11305.9		CZE	0.136
CHE	0.172		POL	11018.2		SWE	0.117
POL	0.153		HUN	10956.5		DNK	0.092
NLD	0.151		SWE	10884.9		ESP	0.084
SVK	0.144		SVK	10804.1		GBR	0.075
HRV	0.143		DNK	10655.2		POL	0.074
GRC	0.143		GBR	10374.8		BEL	0.069
CZE	0.142		BEL	10325.5		NOR	0.065
SRB	0.138		NOR	10292.9		FIN	0.059
FIN	0.124		SVN	9967.9		SVK	0.050
LTU	0.119		UKR	9717.4		HUN	0.043
DNK	0.114		ESP	9712.4		SVN	0.032
ROU	0.110		FIN	9698.3		LTU	0.018
SVN	0.106		HRV	8953.1		RUS	0.018
BGR	0.103		LTU	8916.2		LUX	0.017
NOR	0.100		RUS	8725.4		UKR	0.016
GBR	0.097		SRB	8261.4		PRT	0.015
RUS	0.090		ROU	7820.8		HRV	0.013
BIH	0.074		GRV	7722.9		GRC	0.011
BEL	0.055		BGR	7623.9		BGR	0.009
MNE	0.055		PRT	7223.9		SRB	0.009
ESP	0.053		EST	6918.0		ROU	0.008
MKD	0.041		LVA	6682.3		EST	0.008
ALB	0.040		BIH	6620.9		LVA	0.005
EST	0.036		MKD	6420.2		MKD	0.005
LVA	0.033		LUX	5936.0		BIH	0.005
BLR	0.033		MNE	5736.7		TUR	0.004
TUR	0.022		TUR	5557.9		MNE	0.003
LUX	0.002		BLR	5416.1		BLR	0.003
PRT	0.000		ALB	5173.8		IRL	0.002
IRL	0.000		IRL	3995.7		ALB	0.002
MDA	0.000		MDA	1957.2		MLT	0.002
MLT	0.000		MLT	1899.7		MDA	0.001

Table 3: Values of current flow betweenness centrality, current flow closeness centrality and laplacian centrality of the network.

The values of the edge current flow betweenness centrality are not fully reported in this relation because there are too many, the first four edges are: SWE$<->$FIN=0.078, ITA$<->$FRA=0.075, CHE$<->$DEU=0.074, ITA$<->$CHE=0.071.

By running the code, you will be able to view all the values that are logged to the terminal.

4 Simulation of the electricity grid in 2050

In the second part of the project, when running the file "Evolution.py," you will be able to observe an initial plot of the European grid. This plot considers not the energy production of the states but rather the energy consumption, taking into account electricity exchange through the edges. Following this, a simulation presents a potential scenario illustrating the transition towards greener electricity generation in Europe. However, to proceed with the simulation, certain assumptions must be made.

There are numerous scenarios regarding the electricity consumption of Europe in 2050. In this project, I have chosen a median value that assumes an increment of 40% in consumption for simplicity. For this reason, the consumption of each state has been increased by this percentage.

Subsequently, the coal, oil, and gas supply are eliminated, and the deficit of each state is calculated, accounting for the increment in consumption that each state needs to meet. In order to distribute the new power required to fill this gap, two parameters are considered: the PIL (Product of Internal Load) of the states and the closeness centrality of the states, which is calculated on an undirected, unweighted network of European links.

At this stage, we have identified surplus or deficit in electricity for each state. The sum of all contributions is naturally zero. Prior to simulating the creation of network links, adjustments are made to the balance. A function is implemented to restrict states from importing more than 5% of their own energy consumption and exporting more than 15% (these values may seem small, but with the increase in consumption, trade between states leads to a significant development of interconnections).

Now, the algorithm for the propagation of electricity can begin, creating the links of the network. The criteria are as follows: a state with surplus energy supply exports a single unit of electricity (set at 100 W) to neighboring states experiencing a deficit. If there are no neighbors with a deficit, the algorithm allows exporting to states that don't have a deficit, enabling them to export in subsequent iterations. The algorithm runs recursively until all nodes in the network have a neutral energy supply budget (fig 4).

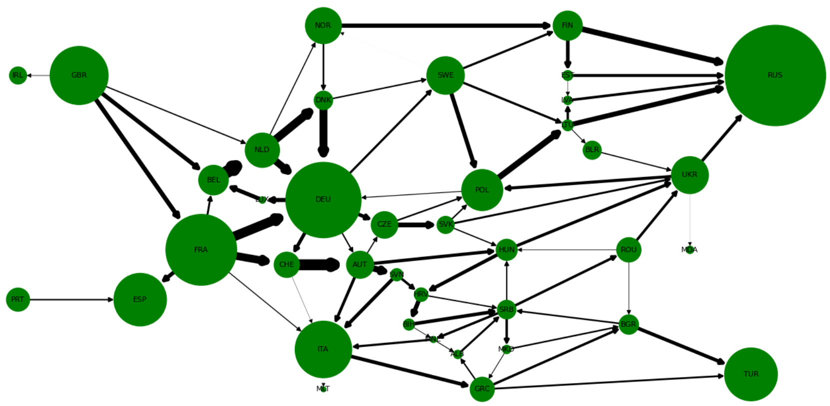

Figure 4: Network of the European electricity grid after the simulation (for a better visualization run the code).

The final step involves determining the energy sources that each state needs to implement. Among the available technologies, solar energy, wind energy, and nuclear energy are the only scalable and clean options. Solar and wind energy are not programmable source, so without a storage technologies that can satisfy the European need (today a technology that can store this amount of energy doesn't exist) we need to use also a clean and programmable source like nuclear energy. Today Germany, which have an amount of solar and wind near to 50%, starts to have some problems in managing the stability of his electric grid and they starts to need a quite big amount of storage technologies for his managing that now are satisfied by gas and coal.

Based on these considerations, I propose that 50% of the energy mix be met by solar and wind energy, while the remaining portion is fulfilled by nuclear power. It is important to acknowledge that this is a generalized approach, as each state may have varying conditions and geographical characteristics that allow for a larger or smaller reliance on solar and wind energy.

In Table 4, you will find the power allocation and total consumption for each state resulting from the simulation. If you run the code, on the terminal are logged the weight of all the links of the networks.

For the calculation of the new power I considered the mean capacity factor in Europe for each energy source: 1 TWh for each GW of installed solar capacity, 2.5 TWh for each GW of installed wind capacity, and 7.5 TWh for each GW of installed nuclear capacity. For the same reasons mentioned before, these values are generalized, as each state may have different characteristics. For instance, Italy may have a significant amount of solar capacity but a smaller wind capacity, while the United Kingdom may have a substantial wind capacity but a lower solar capacity.

Nation	Solar/Wind (GW)	Nuclear (GW)	Total consumption (TWh)
ALB	1.92-4.8	0.0	10.5
AUT	19.76-49.40	0.0	105.9
BIH	3.24-8.10	1.23	18.2
BEL	23.92-59.80	0.0	126.5
BGR	10.52-26.30	1.19	54.3
BLR	10.04-25.10	2.93	47.8
CHE	17.76344.40	0.0	92.3
CZE	21.80-54.50	2.05	101.9
DEU	84.04-210.10	52.01	817.0
DNK	3.08-7.70	2.23	49.6
EST	2.36-5.90	1.09	14.5
ESP	45.40-113.50	18.31	397.6
FIN	26.56-66.40	0.0	123.2
FRA	157.76-394.40	0.0	721.2
GBR	84.88-212.20	5.71	485.2
GRC	14.84-37.10	2.60	84.5
HRV	4.28-10.70	0.35	26.8
HUN	12.80-32.00	0.0	64.4
IRL	4.28-10.70	3.21	42.4
ITA	65.92-164.80	22.44	460.5
LTU	2.60-6.50	0.0	17.4
LUX	1.00-2.50	0.0	6.2
LVA	1.88-4.70	0.24	10.5
MDA	1.48-3.70	0.51	8.2
MNE	0.96-2.40	0.12	5.6
MKD	1.84-4.60	0.39	10.3
MLT	0.60-1.50	0.19	3.6
NLD	32.28-80.70	6.92	169.8
NOR	43.12-107.80	0.0	187.0
POL	37.88-94.70	17.44	242.8
PRT	12.08-30.20	2.15	77.5
ROU	15.44-38.60	1.03	85.6
SRB	10.20-25.50	1.67	50.0
RUS	260.64-651.60	66.64	1449.7
SWE	40.76-101.90	0.0	203.4
SVN	3.84-9.60	0.40	21.9
SVK	8.04-20.10	0.0	42.4
TUR	61.92-154.80	21.81	401.8
UKR	34.68-86.70	4.65	197.3

Table 4: Values of current flow betweenness centrality, current flow closeness centrality and laplacian centrality of the network.

5 Conclusion

In this project, an analysis of the European power grid was conducted, focusing on electricity exchanges between countries and evaluating decarbonization scenarios. The analysis consisted of two distinct parts: the first part utilized real data to construct networks and compare the pre-COVID-19 (2017-2019) electricity network with the network during the pandemic (2020) to assess the disruptions caused by the virus on the European power system. The second part of the project involved simulation to reconstruct and reorganize the energy mix of European countries by phasing out the most polluting sources (coal, oil, gas) in order to achieve a clean energy transition by 2050.

From the analysis of the networks constructed using real data, it was observed that during the year of the COVID-19 pandemic, there was a 3.9% reduction in total energy production and an 11.0% decrease in carbon intensity. This suggests that during the pandemic, there was a decline in energy production and a reduction in carbon intensity.

The analysis using the HITS algorithm allowed for the identification of nodes with electricity surplus (hubs) and nodes with electricity deficit (authorities). This information can be useful in understanding the interdependencies among European countries and the role of each node in the power grid.

In the simulation of a clean energy transition, certain assumptions and approximations were made regarding future energy production and the acceptable energy mix for European countries. The results of the simulation will provide insights into how to reorganize electricity in Europe to reduce environmental impact and achieve decarbonization goals by 2050.

In conclusion, this project provides an in-depth analysis of electricity exchanges among European countries, assessing the impact of the COVID-19 pandemic on the power system and proposing clean energy transition scenarios. This information can be evaluate for policy decisions and future strategies in managing and optimizing the European power system, promoting greater sustainability and reducing carbon emissions.

References

[1] "www.energygraph.info,"

[2] "https://www.kaggle.com/datasets/prateekmaj21/electricity-production-by-source-world,"

[3] "https://www.kaggle.com/datasets/donjoeml/energy-consumption-and-generation-in-the-globe,"

[4] "https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf#page=7,"

[5] "https://networkx.org/documentation/stable/reference/algorithms/generated/networkx.algorithms.link_analysis.hits_alg.hits.html#hits,"

[6] "https://networkx.org/documentation/stable/reference/algorithms/generated/networkx.algorithms.centrality.current_flow_betweenness_centrality.html#networkx.algorithms.centrality.current_flow_betweenness_centrality,"

[7] "https://www.centiserver.org/centrality/Current-Flow_Betweenness_Centrality/,"

[8] "https://networkx.org/documentation/stable/reference/algorithms/generated/networkx.algorithms.centrality.edge_current_flow_betweenness_centrality.html#networkx.algorithms.centrality.edge_current_flow_betweenness_centrality,"

[9] "https://networkx.org/documentation/stable/reference/algorithms/generated/networkx.algorithms.centrality.current_flow_closeness_centrality.html#networkx.algorithms.centrality.current_flow_closeness_centrality,"

[10] "https://www.centiserver.org/centrality/Current-Flow_Closeness_Centrality/,"

[11] "https://networkx.org/documentation/stable/reference/algorithms/generated/networkx.algorithms.centrality.laplacian_centrality.html#networkx.algorithms.centrality.laplacian_centrality,"

[12] "https://www.centiserver.org/centrality/Laplacian_Centrality/,"