Complex system modelling of power grid

Dynamic computational model of power grid function and failure

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ABSTRACT

The power grid is a critical infrastructure that provides electricity to homes, businesses, and industries. Despite its design for reliability, power grid failures are still common due to various factors such as natural disasters, equipment malfunctions, solar weather, and cyber-attacks. Power grid failures have significant economic and social impacts, including financial loss, public safety concerns, and critical service disruptions. This report explores power grids' functions and failures, identifies key challenges and opportunities for improving their reliability and resilience, and models power grids to investigate possible failures.

Ensuring the stability of the power grid is critical for maintaining reliable power delivery and avoiding negative consequences such as power outages. This report proposes an agent-based power grid simulation that models power capacity, demand, and power sharing between neighbouring nodes to better understand the power grid's behaviour and prevent or mitigate power outages. The simulation uses NetworkX graphs, where node appearance, edge colour, and labels are crucial in conveying useful and easy-to-interpret information. The simulation considers multiple cities connected to the power grid, where each city's power demands are represented by a sine wave with given parameters that fluctuate throughout the range of testing. A blackout is classified as a situation where a city receives less than 40% of its desired power, while a brownout occurs when a city receives between 40% to 85% of its desired power.

The simulation results show that the ratio between a power grid's capacity and demand is crucial in determining the stability and reliability of the grid. When the demand for electricity exceeds the power grid's capacity, the system becomes strained, and the risk of blackouts and brownouts increases significantly. Therefore, ensuring that the grid's capacity is sufficiently higher than the demand to maintain system stability during peak usage is essential.

KEYWORDS

Power grid, infrastructure, electricity, system failures, equipment malfunctions, transmission line, generating station, brownout, blackout, power supply failure, modelling, cellular automata, agent-based models, complex systems, NetworkX, Python.

1 INTRODUCTION

The power grid is a critical infrastructure for providing electricity to homes, businesses, and industries. Despite being designed to provide reliable power, system failures are still common. Various factors, including natural disasters, equipment malfunctions, solar weather, and cyber-attacks, can cause these failures [1]. A power grid failure can have significant economic and social impacts, including financial loss for businesses, public safety concerns, and disruption to critical services [1]. As such, it is essential to simulate and analyze power grid failures to develop effective strategies for mitigating the risks and minimizing their impacts. This report explores power grids' functions and failures and identifies key challenges and opportunities for improving their reliability and resilience.

The stability of the power grid is critically important because a stable power grid ensures that electricity is reliably delivered to customers. For power grids, the failure of a transmission line or generating station could significantly affect regular operations and potentially result in a brownout or blackout [3]. Brownouts are a voltage reduction of the grid, while blackouts are a complete power supply failure [3]; Brownouts and blackouts can have severe consequences for individuals, businesses, and critical infrastructure [1]. This report aims to model power grids and investigate possible failures.

1.1 Problem statement.

When things go wrong in a power grid, it can be difficult to restore power quickly, especially if the outage affects a large area or the cause of the outage is not immediately apparent. Power outages can also be expensive for power companies; Outages can result in regulatory fines if the outage is due to a failure to maintain the grid or adhere to safety standards. While outages can be expensive for power companies, according to a literature review by Atputharajah et al., "It is also not cost effective to make the system to be stable for all possible outages" [2].

Therefore, ensuring the stability of the power grid is critical to maintaining reliable power delivery and avoiding the negative consequences of power outages. Modelling and analyzing the stability of the power grid can aid in identifying potential risks; thus, proactive measures can be put into place to prevent outages and maintain grid stability.

1.2 Description of approach.

Power grids are incredibly complex systems and thus can be difficult to model precisely. This report uses a simplified agent-based model approach. The approach is as follows:

(1) Define the parameters.
(2) Simulate power grid dynamics.
(3) Analyze the system behaviour
(4) Experiment with parameter values
(5) Validate the model.

The initial step in modelling the system is defining the system parameters. The model consists of generators, transmission lines, and consumers. The next step in the approach is simulating the power grid dynamics, in this case, the interactions between the generators, transmission lines, and consumers. The generators produce at a rate dependent on the demand of the consumers. It was then essential to analyze the system behaviour and experiment with various parameter values; These are further discussed in the Execution section of the report. Lastly, the model is validated by comparing the results to related work and discussing the accuracy of the model.

2 RELATED WORK

Microgrids. The article “Multi-platform real-time microgrid simulation testbed with hierarchical control of distributed energy resources featuring energy storage balancing“discusses the challenges of testing new strategies for small-scale renewable power generation by simulating microgrids [5]. Whereas many large power grids rely on a few generators for a comparatively large number of cities, microgrids are scaled-down versions. These can help small cities manage power more efficiently by acting as both a local source of generation and a component of a decentralized electricity group. Integrating this into our project, with more time, we believe that expanding the simulation and comparing the rate of brownouts and blackouts when using a large centralized power grid to the same rate while using a higher quantity of microgrids could lead to insights into the strengths and weaknesses of small vs. large scale power distribution techniques.

Stability and Resilience. “The effect of renewable energy incorporation on power grid stability and resilience” is an article that provides a framework for analyzing microgrids and shows that increased uptake of renewable generators can adversely affect grid robustness since their power outputs are highly clustered in time, despite their spatially distributed nature [6]. This results in grids handling large power flows, rendering them fragile to catastrophic failures. The paper uses dynamical models, household power consumption, and photovoltaic generation data to show how these characteristics vary with the distribution level. It is shown that resilience exhibits daily oscillations as the grid’s effective structure and the power demand fluctuate.

The article can be used to improve the agent-based power grid model by incorporating the effects of renewable energy sources on the stability and resilience of the power grid. The paper provides a framework for analyzing microgrids. It shows that increased uptake of renewable generators can adversely affect grid robustness since their power outputs are highly clustered in time, despite their spatially distributed nature. By incorporating these effects into the agent-based power grid model, it is possible to identify the most vulnerable parts of the network and take appropriate measures to improve its resilience.

Criticality. The article “New centrality measures for assessing smart grid vulnerabilities and predicting brownouts and blackouts” proposes mathematical models based on the electrical properties of smart grids for conducting vulnerability analyses and predicting brownouts and blackouts [3]. These models can be used to assess the overall vulnerability of the network. The article outlines the criticality of various nodes apart of power grids. As discussed in Next Steps, criticality is an essential next step in analyzing load-shedding and its effect on real-life power grid systems. The article can help assess the overall vulnerability of the power grid model and identify parts of the network that require attention.

3 METHODOLOGY AND DESIGN

3.1 Software Methodology

In this power grid simulation, the power capacity of each generator is determined by dividing the overall capacity equally among them. For example, if the overall capacity of the grid is 20,000 MW, then each generator will receive an equal share of 10,000 MW. This simplification is helpful because the overall functioning of the power grid is more important than any individual generator.

Multiple cities are connected to the power grid, and each city is also connected to its adjacent neighbours. The power demands of each city are represented by a sine wave with given parameters, causing them to fluctuate throughout the range of testing. If a city’s power demand exceeds the capacity of its assigned generator, the city will draw all available power from that generator and then attempt to pull power from its neighbours’ generators. This is achieved by increasing the demand of the neighbour to pull more power from its respective generator, which is then sent over to the original demanding city.

In this simulation, a blackout is classified as a situation in which a city receives less than 40% of its desired power, while a brownout occurs when a city receives between 40% to 85% of its desired power. By using this model, we can better understand how the power grid behaves and how power outages can be prevented or mitigated in different scenarios.

The PowerGrid Agent class plays an essential role in our simulation by serving as a parent class for two key subclasses: the GeneratorAgent and the CityAgent. This parent class provides each of its children classes with important attributes such as a name and a graph, making it easier to keep track of nodes in the power grid network. Specifically, each generator node in the grid is assigned an instance of the GeneratorAgent class, which includes crucial information such as overall capacity, current power output, and on/off status.

To make it easier to work with these attributes, the GeneratorAgent class includes a set of functions that allow for easy retrieval and setting of these values. Additionally, the class includes a function that calculates and returns the remaining capacity based on the difference between the capacity and power output. This information is crucial for determining the status of the power grid and identifying potential problems such as blackouts or brownouts. By encapsulating this functionality within the GeneratorAgent class, we can easily manipulate and monitor the performance of individual generator nodes, as well as the overall health of the power grid network.

The CityAgent class is responsible for managing the attributes and methods of each city node in the simulation. These attributes include the city's power demand, consumption, and the amount of power it shares with its neighbours. Its methods enable it to consume power from its associated generator and neighbouring cities. When the city's power demand exceeds what the associated generator can supply, the consume power method generates a list of all generators connected to the city and attempts to draw power from them. However, the consume_from_neighbour() method is called if this demand remains unmet. This method first increases the power demand of each of the city's direct neighbours and attempts to draw extra power from them. If this is not enough, it continues to increase the demand of the neighbours' neighbours and so on until all connected generators are at maximum output. By iterating through the network of connected cities and generators in this way, the simulation accurately models the complex interplay between power supply and demand in a realistic power grid. However, the method does not work as expected and is discussed soon.

The PowerGrid class is the backbone of the entire system. It holds all the important attributes, including the position of each node, the edges connecting them, and dictionaries for both generator and city agents. To initialize the power grid, it assigns each generator and city a name and position, then connects their edges. The PowerGrid class also features methods to add generator and city agents to the grid and to draw the graph. To keep the grid up-to-date, the class includes an update_edge_value() function that redraws the edges in the graph with the latest values and a generate_demand_changes() method that updates the demand of each city based on a sine wave. To ensure the grid's stability, it has a function to check if all generators are maxed out, and an update_power_grid() function that updates the demand for each city, calls the consume power function for each city, and the consume from neighbours function if needed. This function also collects data on the number of brownouts and blackouts that occur during a particular time step.

Power Sharing. One component that increases the project complexity is modelling the sharing of power consumption between neighbouring nodes. Power sharing is crucial since it is essential to the real power grids being simulated. It was also complex because each node's consumption (or power generation) determines the direction of the power flow and the quantity of power flowing on each edge. Figure 1 and Figure **??** below show an example of this working. To accomplish this, a depth-first search was used to determine which nodes were furthest away from the generators. Then, we started with the nodes with the least neighbouring nodes to reduce the number of dependent nodes we would change for each value we update. To calculate the power the node would draw from its neighbours, the nodes' power demands are passed on to the next neighbour (splitting the load evenly if there was more than one). The method then worked up from the furthest away nodes to the generators, where two options would occur. Either the demand on the generators was more significant than the maximum power they could produce, resulting in a blackout or brownout. Alternatively, the demand was less than the supply, and everything was fine.

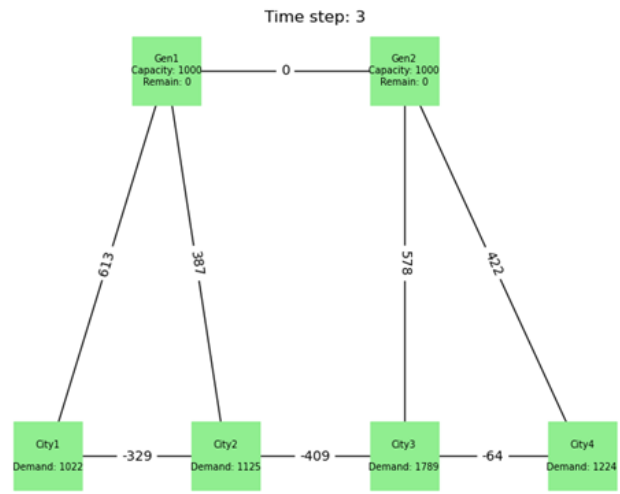

Figure 1: Blackout occurs when there's not enough capacity to supply demand.

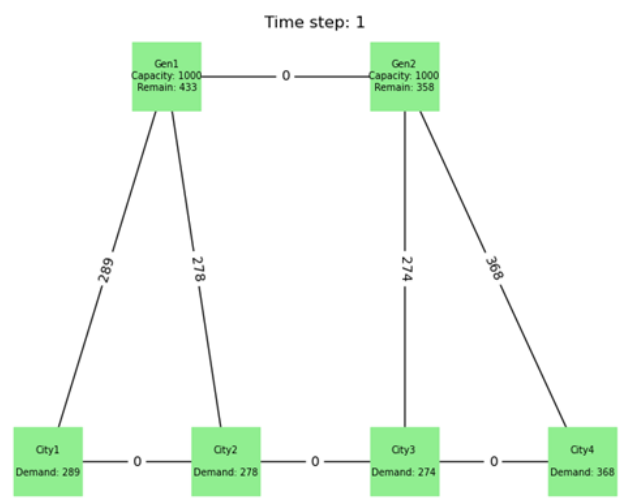

Figure 2: A time step when there is no need to borrow power from the neighbors.

The ratio between a power grid's capacity and demand is a crucial factor in determining the stability and reliability of the grid. When the electricity demand exceeds the power grid's capacity, the system becomes strained, and the risk of blackouts and brownouts increases significantly. Therefore, ensuring that the grid's capacity is sufficiently higher than the demand to maintain system stability during peak usage is essential. However, after passing a certain ratio, it becomes increasingly expensive to maintain the necessary capacity level, and the marginal benefits of additional capacity diminish. Therefore, finding a balance between the capacity and demand that maximizes the grid's stability without incurring undue costs is crucial.

The simulation for this study involves creating a power grid with multiple generators and city agents. The capacity/demand ratio is varied by adjusting the generators' capacity relative to the cities' demand. The simulation is then run for a set time period, during which the power grid is updated with a demand of a fixed value, and the probability of blackouts and brownouts is recorded. The process is repeated several times to obtain an average probability of blackouts and brownouts. The results are then compiled into two lists: one for the average blackout probability and the other for the average brownout probability, with each entry corresponding to a specific capacity/demand ratio.

3.2 Visual Design

In an agent-based power grid simulation, the visual appearance of NetworkX graphs is crucial in conveying useful and easy-to-interpret information. It is essential to consider various aspects of graph visualization, including node appearance, edge colour, and labels. We can easily differentiate between producer and consumer nodes using graphical images for nodes. Similarly, edge colours can indicate the voltage level of the transmission lines, while varying edge thickness can represent the line capacity. Furthermore, labels can provide additional information, including transmission voltage, current generator production, city consumption and name. Figure 3 shows a proposed visual representation that was created during the design phase. Altering the visual appearance of NetworkX graphs allows a more informative and intuitive representation of the power grid simulation.

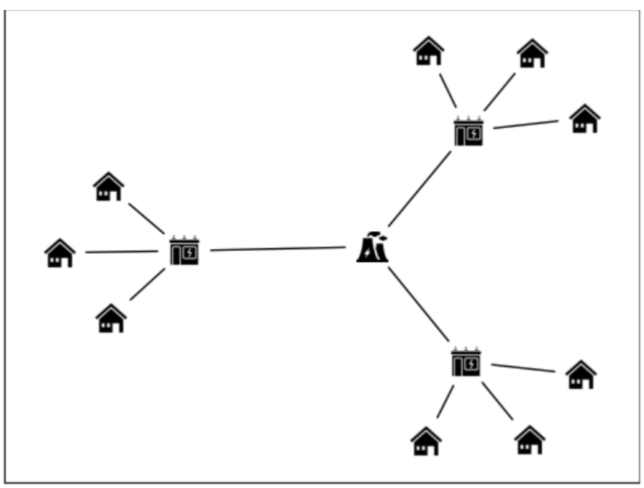

Figure 3: A mock-up produced during the design phase.

4 EXECUTION OF SIMULATION.

This is where the execution goes.

consume_from_neighours(). Something that went wrong was the implementation of the consume from neighbours function. The function was supposed to distribute the power needed by the consumers (nodes) along the edges of the graph so that either each node's demands were satisfied or they were not satisfied, and there was a blackout or brownout that occurred. The first problem we encountered was underestimating the amount of work an algorithm like this needs. We started by just looking at the nodes as a list and calculating the changes in power consumption of adjacent nodes on that list. We did not realize this was a dead end until late in development and had to start over. This would not work because once one changes a node's power consumption based on its neighbours, an adjacent node could change it right back, and there was no way to tell nodes two nodes apart to share the power from the commonly adjacent node. So this created a situation where nodes that were assessed later overwrote the previous changes of earlier nodes because the order we assessed the nodes was random. Once we switched to a tree structure for checking the nodes and implemented Dijkstra's algorithm (by using the nx.shortest_path_length() function), we solved that problem but encountered another problem. The shortest_path_length function is usually used with a single starting point to figure out the shortest path lengths to other points of interest. However, what we really want is the shortest path lengths with multiple starting points since we planned to have multiple generators (which are the starting points). This complicates things, and we would need to develop some more logic to incorporate this new constraint into the code. However, we still need to make this change, so our model is only good at modelling micrograds with only one generator.

An improvement that we would make if we had more time was to implement the support for multiple generators. The way we might go about that is to run the shortest path length function for each generator and then conglomerate the shortest paths so the true depth is the shortest path from any generator, not just one. With this, the algorithm could handle multiple generators assuming no other problems exist.

Stability. The stability of a power grid is heavily influenced by the ratio between its capacity and demand. To study this relationship, a simulation was set up with an initial capacity and demand of 20,000 MW, reflecting Ontario's monthly mean power demand. The ratio between capacity and demand was then varied to simulate blackout and brownout probabilities over a set time period. Figure 4 shows that assuming perfect conditions where no generator is offline, a ratio of 1 (equal capacity and demand) results in no blackouts. However, this is not a realistic scenario, given the possibility of generators being offline for maintenance or other reasons. Examining Figure 5, which plots the average brownout probability against the capacity/demand ratio, a high probability of brownout (up to 23%) was observed at a ratio of 1. These findings highlight the importance of carefully balancing a power grid's capacity and demand to ensure stable and reliable operation. Once the ratio surpasses a certain threshold, the costs of increasing capacity may outweigh the benefits in terms of improved stability.

The stability of a power grid is crucially dependent on the balance between its capacity and demand. The graph in Figure 6 highlights that exceeding a ratio of approximately 1.30 (26,000 MW to 20,000 MW) can lead to diminishing returns in terms of adding more capacity to the grid. However, while it's essential to find an optimal ratio, it's equally critical to maintain redundancy in the system. For instance, Ontario's mean power demand is approximately 20,000 MW [4], but the total capacity is 40,200 MW. However, this

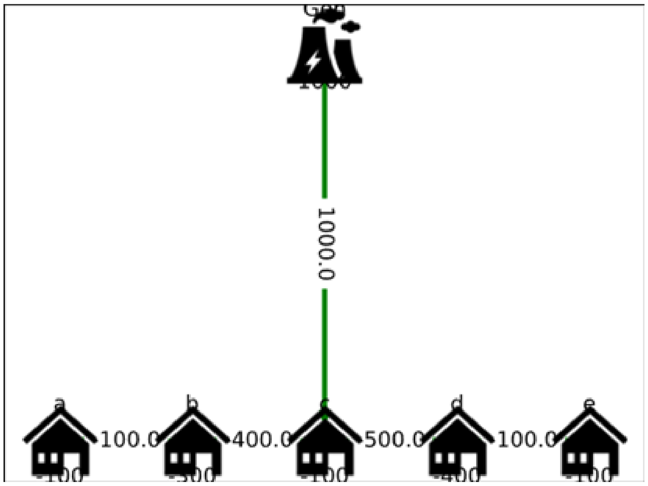

Figure 4: Microgrid implementation with icons attached.

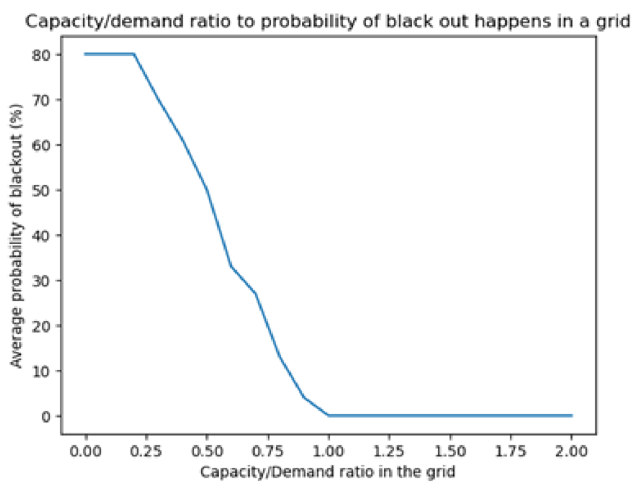

Figure 5: Capacity/demand ratio of probability of blackout happens in grid.

doesn't imply that all the power can be used at once due to various factors like maintenance or weather conditions. Reserves are necessary to ensure that the forecasted demand can be supplied with a high level of reliability. The peak capacity in 2021 was 25,316 MW [4], much lower than the total capacity. This was because of seasonal rates, planned outages, and the capacity of energy-limited resources. While having a theoretical maximum capacity is desirable, it's essential to have a reserve in case of unpredictable weather or disasters.

The model used in this study simulates the fluctuation of demand in cities connected to the power grid, with demand varying between 75% to 150% of the base demand of 20,000 MW. While the daily power demand typically falls within this range, there is always a chance that an external or internal event could cause demand to surge beyond these limits. In such a scenario, the power draw on the grid could reach a critical level, such as 30,000 MW (150% of 20,000 MW). This highlights the importance of redundancy within the power grid, as unexpected events can quickly push demand beyond

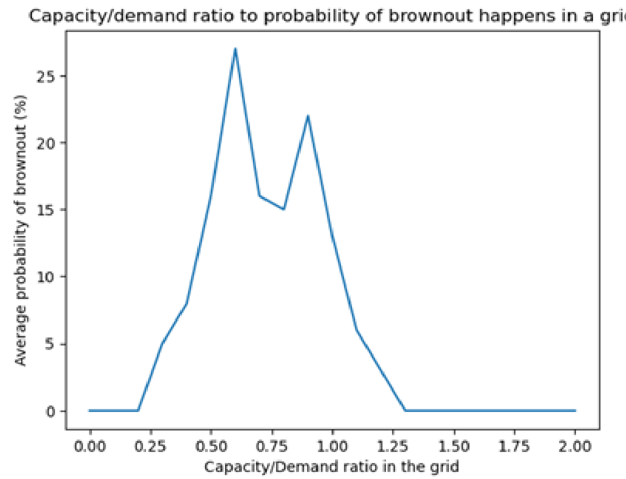

Figure 6: Capacity/demand ratio to probability of brownout happens in a grid.

its normal limits. These events can include weather-related disruptions or internal issues within the grid's systems. By accounting for these possibilities and ensuring sufficient capacity, the power grid can maintain stability and reliability even during unpredictable events.

The ratio between a power grid's capacity and demand is a critical factor in ensuring the stability and reliability of the system. While it's important to find an optimal ratio, this model does not account for the many variables that are also essential to the grid's operation, such as transmission line capacity or the probability of any generator turning off randomly. Thus, the results of this study provide a valuable starting point for understanding the impact of capacity and demand ratios on the grid's stability, but they should not be taken as an exhaustive assessment of the system. It's crucial to maintain redundancy in the system and account for unexpected events that can quickly push demand beyond its normal limits. By doing so, the power grid can continue to operate with a high level of reliability and stability, even in the face of unpredictable events.

5 NEXT STEPS AND CONCLUSION

5.1 Next steps

The current iteration of the model is an abstract representation of a power grid. The next steps include several essential considerations to develop a more realistic power grid representation. First, adding redundancies to the model will be necessary to represent current power grids. By adding redundancy, the power grid model will be more robust and able to handle unexpected events. Load shedding should also be incorporated into the model; Power grids use load shedding to reduce demand during periods of high stress. Adding load shedding will require the incorporation of consumer criticality and then developing a strategy for shedding non-essential loads. By incorporating load shedding, the model will be more realistic and able to simulate real-world scenarios. Overall, these next steps will require additional research and development, but they are necessary for improving the accuracy and reliability of the power grid model. By adding redundant systems, load shedding, and increasing the component and scale of the model, it will become a more practical and valuable tool for understanding the behaviour of the power grid.

5.2 Conclusion

In conclusion, the power grid is a crucial infrastructure that provides electricity to homes, businesses, and industries. Despite its critical role in our daily lives, power grid failures are common, and they can result from various factors such as natural disasters, equipment malfunctions, solar weather, and cyber-attacks. Power outages can have significant economic and social impacts, including financial loss for businesses, public safety concerns, and disruption to critical services. To mitigate these risks, it is essential to simulate and analyze power grid failures to develop effective strategies for improving their reliability and resilience.

This report has explored power grids' functions and failures, identified key challenges and opportunities for improving their reliability and resilience, and presented a simulation model that can aid in identifying potential risks and implementing proactive measures to prevent outages and maintain grid stability. The model's methodology involved an agent-based and graph power grid simulation, where the overall capacity and demand are set to be the same – 20,000 MW. The simulation also considered multiple cities connected to the power grid, and each city as connected to its adjacent neighbours, representing the power demands of each city by a sine wave with a given (as realistic as possible) parameter with a time cycle of 10 instead of 24, for ease of simulation, causing them to fluctuate throughout the range of testing.

The simulation's power-sharing component increased the project complexity but was essential in modelling the real power grids, as it determines the direction of the power flow and the quantity of power flowing on each edge of the graph. Furthermore, this report also highlights the importance of ensuring that the grid's capacity is sufficiently higher than the demand of the grid to maintain its stability, reliability and resiliency.

Overall, the simulation model presented in this report offers a more informative and intuitive representation of power grid simulation, allowing for a better understanding of how the power grid behaves and how power outages can be prevented or mitigated in different scenarios. Therefore, this model can be useful for students to learn about a couple of aspects of the power grid and boost their understanding. Renewable and clean energy are hot topics when this report is being written and will remain to be so for a long time to come; hence, understanding how power is moved in a complicated and interconnected manner will help prepare for the coming shifts in energy resources in the world.

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