Maintaining Ukraine Energy Infrastructure

ECE 4320, Fall Semester of 2022

Final Course Project

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Section 1: Executive Summary

As of February in the year 2022, Russia invaded Ukraine, and a war has been ongoing between them since 2014. Russia has had the stronger military and many bombing tactics. The Ukrainian energy infrastructure has been severely targeted, weakening the country's military and civilian life. The Ukrainian Defense Ministry is tasked with defending this infrastructure, and they are guided by advisors.

Having the position of advisors to the Ukrainian Defense Ministry, methods of defending the energy infrastructure are to be obtained and reported to the ministry. Stations (buses) with relative high power generation and demand, overall, are the targets of the Russian bombing strikes. Placing defense resources on lines which are connected to these stations, will yield the lowest percent of expected load shedding for the Ukrainian energy infrastructure.

Section 2: Ukraine Energy Crisis Introduction

Economic disputes between Russia and Ukraine have been long ongoing. Russia is the country with a stronger military, having to their advantage unused weapons such as missiles and artillery vehicles from past wars, and a large number of troops. To their advantage, is also a functional power grid, which on the frontline, is mainly useful for the progression of military tactics through communications, and troop recovery by electrically powering hospital. Russian civilian life is also maintained in physical comfort with the presence of the electric energy infrastructure, allowing for soldier shift rotations; this allows for military rejuvenation and rotation while maintaining the frontlines.

Ukraine has suffered many attack-bombings, causing high damage throughout much of the country, including to the cities of Lviv and Kiev, located in Western and central Ukraine, respectively[1]. These two cities are two of the several important cities in Ukraine, where Kiev is the capital [2]. Overall, missiles and self-detonating drones have been used to target energy infrastructures. Half of the country's energy infrastructure is damaged, and the form of damage varies. It includes the loss of electricity, heating (nonelectrical), water, and excessive collateral damage. Organizations such as the World Health Organization conclude the upcoming Ukrainian winter will be survival-based and life-threatening [3]. The civilian lifestyle is troublesome and hectic. Frontline conditions are extremely difficult for the Ukrainian military.

Maintaining the Ukrainian energy infrastructure is a pivotal task. It brings the country one step closer toward victory. Successful defense will result in the military and civilian life being alleviated, in all aspects. Proper military tactics are required for the success of this task.

Section 3: Summary of Attack and Defense Model

Several questions are considered, which will guide the advice given to the Ukrainian Defense Ministry. The question types vary from defense placements, effect of changing defense locations, and general advice for future defense placements. A holistic approach to the situation is of importance.

3.1: Recommended Defense Placements, Corresponding Expected Load Shed

As we do the simulation, we conclude that the Ukrainian Defense Ministry should defend the transmission lines connecting the relatively powerful stations (nodes). The specific defense placements are shown clearly below, in Table 1. To interpret this table: each column represents a condition with certain number of attacks, and each row represents the lines we have put defense on; the numbers inside of the table show how many defenses we locate on the corresponding line under certain condition, and the possible number of defenses ranges from 1 to 3.

	1 attack	2 attacks	3 attacks	4 attacks	5 attacks
Line 2		*1*	*2*	*2*	*2*
Line 3			*1*	*1*	*1*
Line 4	*1*	*1*	*1*	*1*	*2*
Line 11		*1*	*2*	*2*	*2*
Line 12		*1*	*1*	*1*	*2*
Line 13	*2*	*1*	*1*	*1*	*2*
Line 14				*1*	*2*
Line 17		*1*	*1*	*1*	*1*
Line 19					*1*
Line 21				*1*	*1*
Line 25					*1*
Line 26				*1*	*1*
Line 28		*1*	*1*	*1*	*1*
Line 29	*1*		*1*		
Line 30				*2*	*1*
Line 36		*1*	*1*	*1*	
Expected load shed	**3.26%**	**7.33%**	**10.73%**	**10.78%**	**11.79%**

Table 1. Expected load shedding with a given specific set of defended lines and different attack scenarios.

To summarize the table above, the lines of interest are compatible with our conclusion that these lines are connected to stations with high power demand and generation, which are B1, B2, B6, and B20. The power value and type (demand or generated) at each of these stations is 464 MW generated at B1, 585 MW generated at B2, 674 MW generated at B6, and 415 MW demanded at B20. Station B1 is connected to line 2; station B2 is connected to lines 3 and 4; station B6 is connected to lines 12, 13 and 14; station B20 is connected to lines 30 and 11. Additionally, the expected load shedding of each attack scenario is presented in the last row, and it shows that the expected load shed increases with the increment of attack ability. It is also discovered that the defense strategy is similar through the 5 attack scenarios, which is to say that 9 of the 16 lines of interest appear in at least 3 attack scenarios. These 9 lines are color-coded with red. As a result, we recommend the Ukrainian Defense Ministry to focus on all the 16 lines listed in the table, and only do minor modification according to different attack scenarios.

3.2: Sensitivity of Defense Locations

Defense locations are best chosen by identifying the transmission lines which connect to stations with the highest power demand and generation (excluding B15, which has a 422 MW demand). Given a set of attacks ranging from 1 to 5, and identifying and defending the most-important transmission lines (the ones which connect the stations with the highest power), a certain expected load shed will be yielded.

Table 1 lists the best lines to defend, with a certain number of defenses per line, against a given number of opponent attacks. Changing the defended lines will result in a different expected load shed, and the change will be significant. The stations with the highest and the second-to-highest power demand and generation are listed in Table 2.

Demand and Generation Ranking	Stations
Highest	B1, B2, B6, B20
Second-to-highest	B3, B5, B7, B15

Table 2. The stations with highest and second-to-highest power demand and generation.

Stations rated as the highest have power values which range from 415 MW to 674 MW, whereas stations rated as second-to-highest have power values which range from 304 MW to 422 MW. Ideally, as tested with simulations, the majority of the highest-valued stations have lines which are most-worthy of protecting with missile-deterring defenses; the lowest expected load shedding will occur through this method.

Given the defenses are set at the next best locations, at the second-to-highest stations, the expected load shed is altered. This fact is observed in Table 3.

Line Number	1 attack	2 attacks	3 attacks	4 attacks	5 attacks
5	1	1	1	2	1
6	1	1	1	2	2
9			1	1	2
10		1	1	1	2
11				1	2
12		2	2	2	3
15			1	1	2
16		1	1	1	1
35			2	2	2
36	2	2	2	3	3

Expected Load Shed	5.061 %	15.3 %	25.7 %	24.38 %	24.62 %

Table 3. Expected load shedding as a result of protecting the second-to-highest power stations.

Alteration in expected load shedding is observed when comparing Table 3 to Table 1. Although more defenses per line are being used in the generation of Table 3, compared to Table 1, the expected load shed is, yet, greater. The use of more defenses per line should have yielded a better (lower) percent of expected load shed. This is not the case, because the lines which are connected to the second-to-highest in power stations are being defended.

Lines connected to the stations with the highest power demand and generation, are in fact, the best lines to protect. The task at hand is sensitive to the placement of defenses, because a certain set of lines connected to certain power stations are targeted by the opponents; the opponent is a tactical one. The best-case scenario is achieved by protecting the lines which are connected to the stations with the highest power.

3.3: Heuristics for Allocating Defense Resources

After simulating different attacks from Russia. We tried allocating defenses across Ukraine's power grid. After many tests, we concluded that Russia caused the most load shed to Ukraine's grid by targeting their biggest generators. It also seemed that these generators seemed to be central to many numbers of different power demands. Therefore, we minimized the load shed across all outcomes by first placing the bulk of our defenses at the highest generating bus lines. We were able to deter Russia from the western side of the country and minimize the destruction on the eastern end. This is shown in the figure below. For future scenarios we would recommend first defending lines that are connected to the largest generators. Then from here, you should continue to allocate remaining defenses in this manner but can also consider putting defenses in an area which is still vulnerable. Figure 1, below, shows the lowest expected load shedding we were able to achieve using this method.

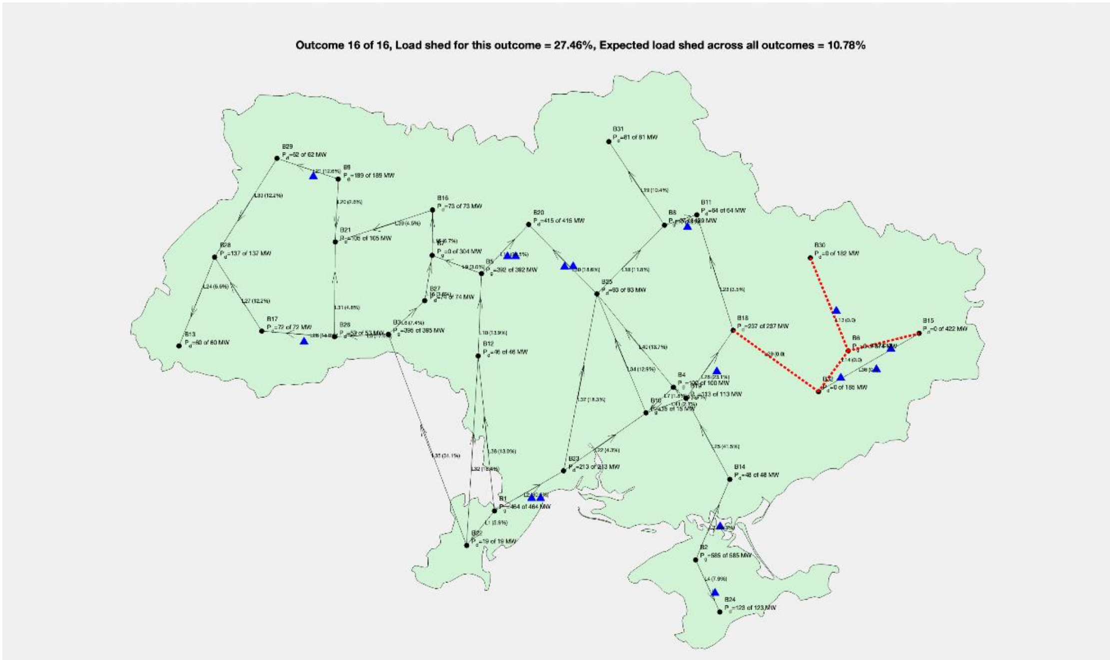

Figure 1. The lowest achieved expected load shedding percent, 10.78 %, given 4 number of attacks.

Section 4: Description of Defense Locations, Given Varying Attacker Capabilities

For our initial results, we set the number of attackers to be 4. Based on the methodology that we used, we can follow the same method and change the number of attackers. After testing the methodology used with number of attackers to be 1,2, and 3. We realized that the lower number of attackers seemed to not target the bigger generators first. I believe that a reason for this may be that even though hitting these areas causes the most load shed, having fewer attacks to target will not do enough damage, hence with fewer attacks they might target smaller areas so that they can do maximum damage. As the number of attacks were increased towards 4, the pattern would trend to placing the first defenses at the bigger generators. There is also a similar trend between three attackers and four attackers in terms of the placement of defenses. By using this methodology, we were also able to keep the overall load shed at around 10%, or below, depending on the number of attackers.

Section 5: Methodological Approach for Defense Placements

We were tasked with reducing the load shed of Russia's attacks by strategically placing defenses across Ukraine. We did this by first understanding what Russia was doing. We know that Russia is trying to attack in a way that will cause the most load shed. Knowing this, we did a simulation with zero defenses across the country. Since there are no defenses, Russia will attack areas that will cause the most destruction. After analyzing the results and seeing where they choose to attack, we can now start to place defenses. We started to place defenses on the areas that are most heavily attacked by Russia, and we continued doing this until we had used up all our defensive resources which was four times the number of attacks which we have set to 4. Hence, we continued this approach until we used our 16 defenses. After we allocated these defenses, we once again analyzed our results. From here, we tested moving around defenses to different areas until we could find the defense allocation which caused the lowest load shedding percent.

Section 6: Limitations Inherent to Results

After simulating different attack scenarios with our optimization methods, we have found an interesting fact, but rather a limitation underlying our defense strategy. Considering the opponent does not alter attacking strategies, the lines which connect to the stations with highest power are, ideally, to be protected, for the lowest percent of expected load shedding. Given the opponent changes tactics, our optimization methods will likely be changed.

Given the event of a real-world war between Russia versus Ukraine war, as it is now ongoing, and an actual power grid layout of Ukraine, the optimization methods will also likely change. The defense placements, number of defense resources, and opponent attack numbers will be the factors which bring-forth the need of change in plans. From an opponent's viewpoint, the plan of action may still be to attack the lines which are connected to the stations with highest power generation and delivery. This will likely be the case, because a high value of power generation signifies an area of high activity, and this may be viewed as a threat to the opponents.

As of now, December of 2022, the West side of Ukraine, the capital, and a large portion of the country has been damaged. Ukraine's Energy Ministry states that bombings left the great majority of consumers without power [1, 2]. In other words, Russia is targeting the majority of cities and villages, they are not only targeting the lines connected to stations with high power. Given this fact, the Ukrainian Defense Ministry may have to gather all citizens in one area, so to safely provide and protect the power generated and delivered to that one area. The downside to this is that it increases vulnerability to attacks, because the opponent will heavily target that area in, particular. The best approach may be to keep the civilians in place and seek troops and supply reinforcements from ally countries.

Possible factors such as opponent foot soldiers walking past important power stations and firing at them with rifles, are also of importance. In the state of North Carolina, Moore County, thousands of consumers were left without power, because entities fired with rifles at substations [4]. Russia may consider this method of attack, given it may be unexpected. The most expected by the Ukrainian Ministry of Defense method of attack, by the Russians, is missile attacks. This is because less soldiers would be wounded through this method.

Section 7: Summary

Given the task of advising the Ukrainian Defense Ministry by seeking the best defense location to minimize the expected load shedding percent, we have found the defense strategy to keep the load shedding as low as 10%. Simulating the attack and defense model in the provided code, we increase our defense location, which is introduced with detail in section 5, by observing the opponent’s attack behavior until we maximize our defense ability. Overall, we have successfully derived suggestions for the Ukrainian Defense Ministry, which will help them to best distribute the defense resources, according to different attack scenarios. The results from the suggestion of protecting the transmission lines which are connected to the stations which have the highest power generation and demand, are shown in the figures below.

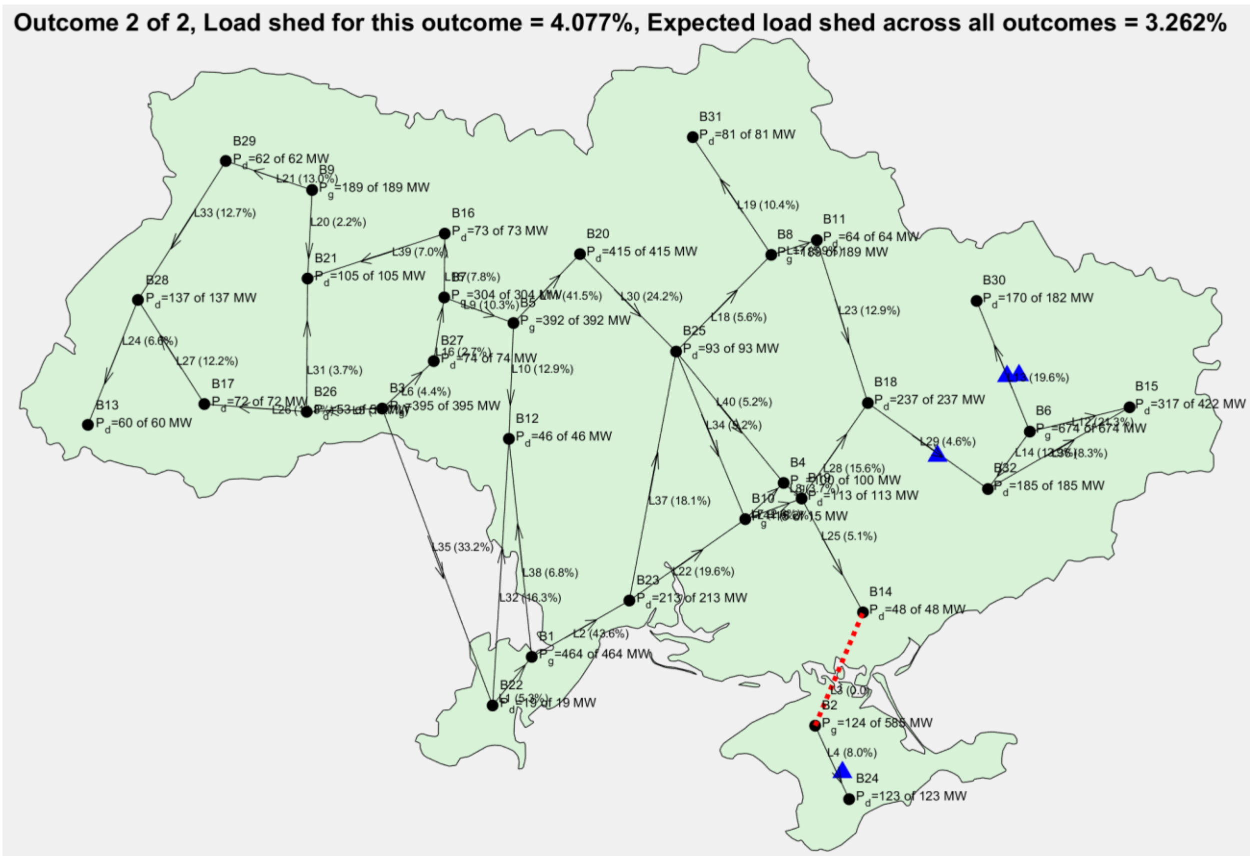

Figure 2. Expected load shedding percent of 3.26 %, given one opponent attack, which allows for four defense allocations.

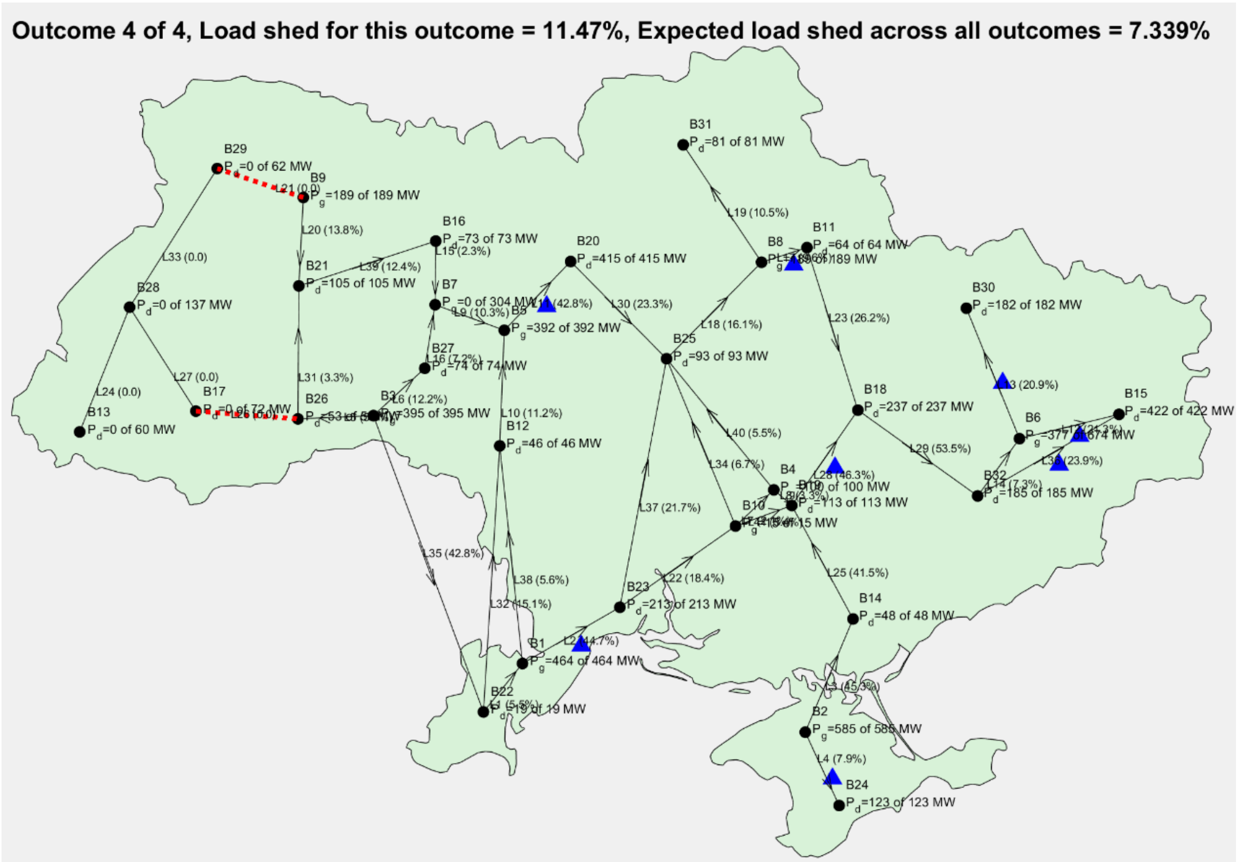

Figure 3. Expected load shedding percent of 7.33%, given two opponent attacks, which allows for eight defense allocations.

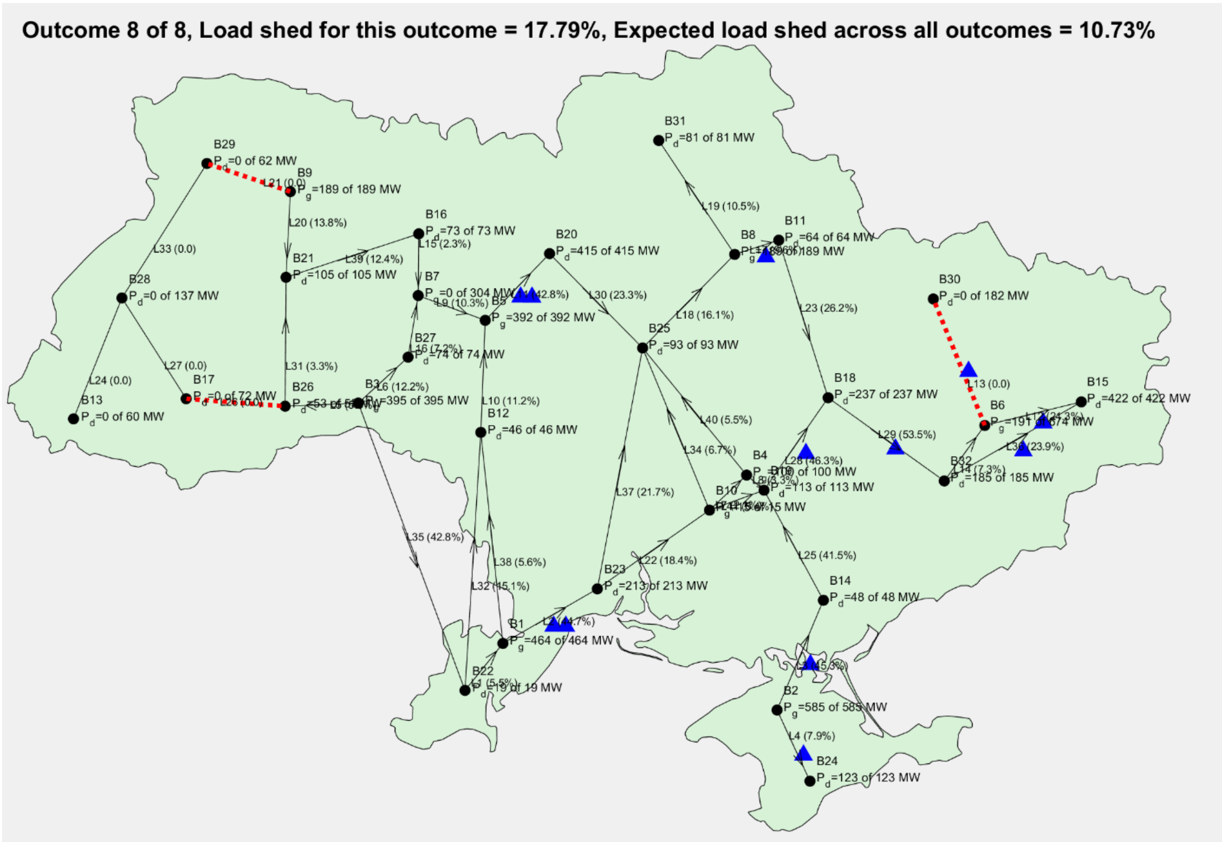

Figure 4. Expected load shedding percent of 10.73%, given three opponent attacks, which allows for 12 defense allocations.

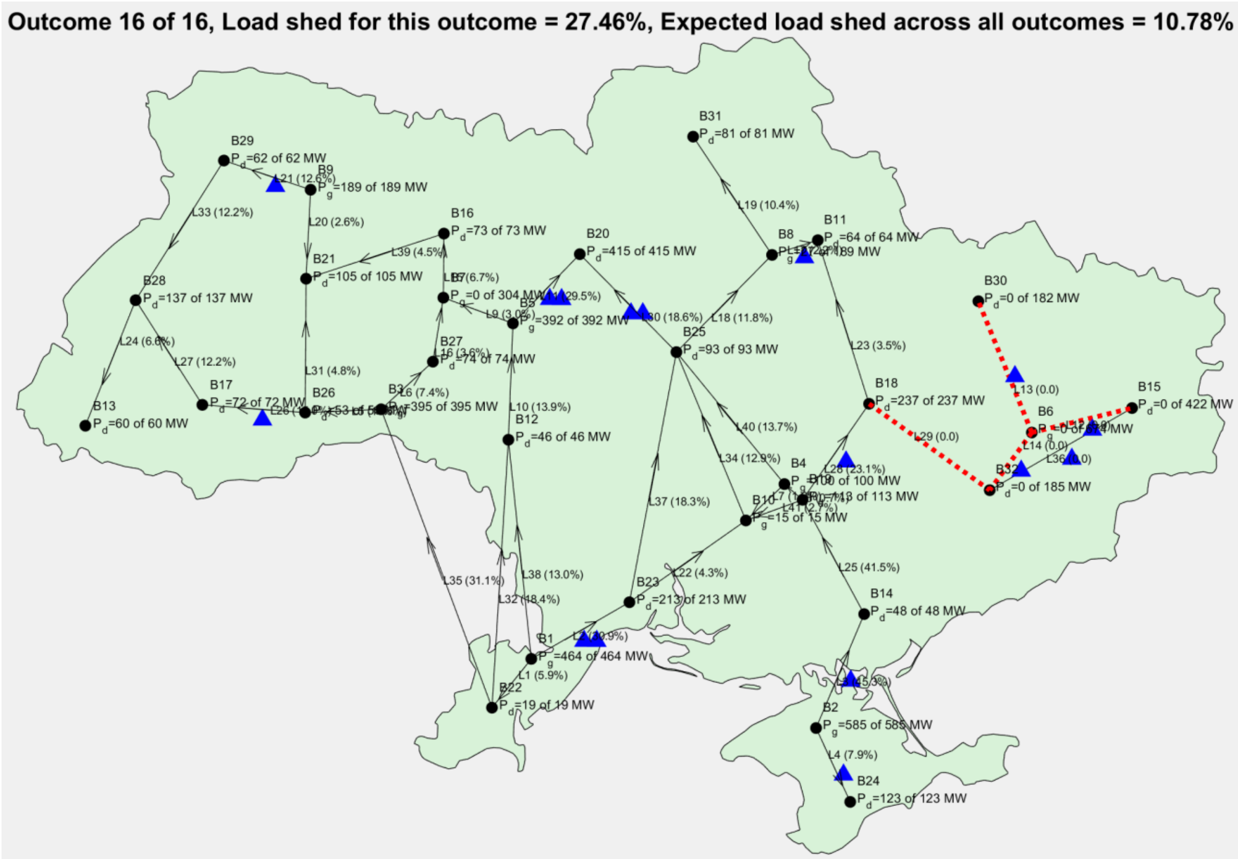

Figure 5. Expected load shedding percent of 10.78%, given 4 opponent attacks, which allows for 16 defense allocations.

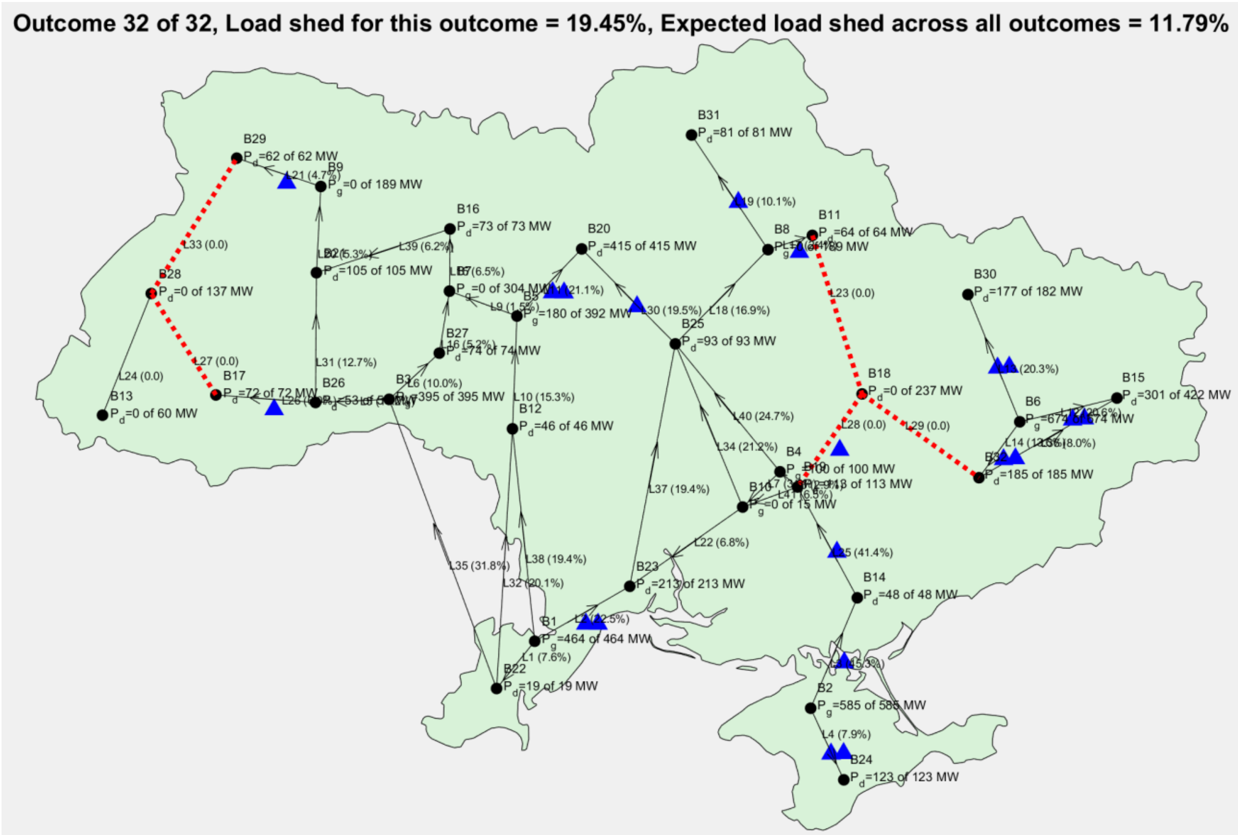

Figure 6. Expected load shedding percent of 11.79%, given 5 opponent attacks, which allows for 20 defense allocations.

Section 8: References

1.) L. Stern, David, et al. “Ukrainian Energy Systems on Brink of Collapse After Weeks of Russian Bombing.” *The Washington Post*, 23 Nov. 2022, www.washingtonpost.com/world/2022/11/23/ukraine-infrastructure-damage-electricity-water-russia. Accessed 7 Dec. 2022.

2.) Map showing the country of Ukraine. Google Maps, https://www.google.com/maps/d/embed?mid=1jguVP8xLYmkwLU2-341vN0zkZTvYmMBx&ll=49.64272042217213%2C30.973338329852727&z=6. Accessed 7 Dec. 2022.

3.) Epstein, Jake. “Russia Has Crippled Half of Ukraine’s Energy Infrastructure and This Winter ‘will Be About Survival,’ Top WHO Official Says.” *INSIDER*, 22 Nov. 2022, www.businessinsider.com/ukraine-energy-infrastructure-crippled-russia-brutal-winter-who-official-says-2022-11. Accessed 5 Dec. 2022.

4.) Heyward, Giulia. “Someone Shot at Substations in North Carolina, Knocking Out Power for Thousands.” *NPR*, 4 Dec. 2022, www.npr.org/2022/12/04/1140647869/power-substations-north-carolina-gunfire-vandalism. Accessed 5 Dec. 2022.

End of Report