Ukranian Power System Defense Model

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Contents

Executive Summary of Results

The following report contains details and analysis of an attack and defense model for the Ukrainian power grid. There are key regions that are prone to attacks, such as Kyiv (line 11), Odessa (line 1 and 2), Crimea (line 3 and 4), Donbas (line 13 and 14) and west Ukraine (line 21 and 26). Protecting these regions by setting up one or more defenses deters the attack away, thereby decreasing the expected load shed across all outcomes. However, it is not guaranteed that a protected region cannot be targeted. As expected, increasing the number of attacks results in an increased expected load shed value. Therefore, increasing the number of defenses for every increment of attacks is crucial in keeping the expected load shed value across all outcomes in check.

1 Ukraine Energy Crisis

The Ukrainian energy crisis occurred amid the Russo-Ukrainian War, which has been ongoing since February 2014 [5]. The conflict escalated in February 2022 as Russia invaded Ukraine's territory in a full-scale warfare. Ever since then, Russian forces have targeted Ukrainian energy infrastructure using both ground forces and aerial attacks in the form of unmanned drones or guided missiles [4]. These relentless attacks have forced millions of Ukrainians into living in complete darkness, depriving them of heat, power and water as the freezing winter nears. Since the war is showing no signs of stoppage, millions of Ukrainians are bracing themselves for a winter with little to no electricity, as power companies struggled to meet increased demand with under-maintained infrastructure [9]. Reportedly, up to 50% of the country's population are experiencing daily power disruptions and that the western part of Ukraine has been hit the hardest [9]. Because the lives of many Ukrainian civilians are endangered, this report aims to provide a thorough analysis of Ukraine's defense strategy against Russian attacks on its energy infrastructure. This is done via a simulation of an attack and defense model, with the goal of minimizing load shedding. The report also aims to evaluate the strengths and weaknesses of different defense strategies, coupled with further considerations of heuristics for future scenarios, as the war continues to go on without an end in sight. The report therefore is contextually consistent, as for years Ukraine has been engaged with the U.S Department of Energy to receive technical expertise on the production, storage and transportation of energy during winter months [1].

2 Summary of Attack and Defense Model

The simulated model of the Ukrainian Power System contains a grid of simulated buses, generators, and transmission lines. The attack model determines which power lines to target based on defense location loaded into the simulation. The goal of the attack is to maximize load shed by cutting off lines that would cause the highest load shed while considering the probability of the success of an attack. The success of an attack accounts for the number of defenses placed at each line. The attacker also has a limited number of locations to attack to simulate a limited number of missiles.

To defend against the simulated attack, a greedy algorithm is a feasible approach to solve this optimization problem. As each defense location is attacked and, subsequently, defended, the connected buses can then be analyzed to determine which connected lines should be the next defense location. The analysis should yield the load shed of each connected line. The line resulting in the lowest load shed should be the next defense location. In theory, a similar optimization could occur with the percentage of success of an attack on the next lines if the success of attack were the priority above load shed. Since the goal, in this case, is to minimize load shed, this algorithm supports that approach.

The methodology for choosing defense locations relied on a Greedy Algorithm, meaning the next defense location is based on the attack location given by the simulation, which is based on the current defense location. For each number of attacks, the scenario with zero defenses is simulated first to be used as a reference point.

Let's consider the case of only one attack and no defenses as an example. It can be seen from figure 13 that the simulation targets line 13. Since only one attack in this scenario, the attack strategy could change depending on the number of attacks.

Using this information, the attack location is appended into the defense locations array before the next iteration of attack is simulated. With one defense location at line 13 the program next targets line 4. A defense is placed there, and the next iteration of attack is simulated. Now there are two defense locations and an attack on line 29. A defense is then added to this location. Then, line 13 is attacked again and so a second defense is placed there. Finally, line 3 is targeted with maximum number of defenses allowed (four) for this case of one attack.

After reaching this conclusion we checked other options to see if we could optimize our work. For example, we tried moving each existing defense location to the targeted line 4, however every defense that we moved to defend line 4 resulted in worse load shedding than leaving the previous configuration. We took this data and

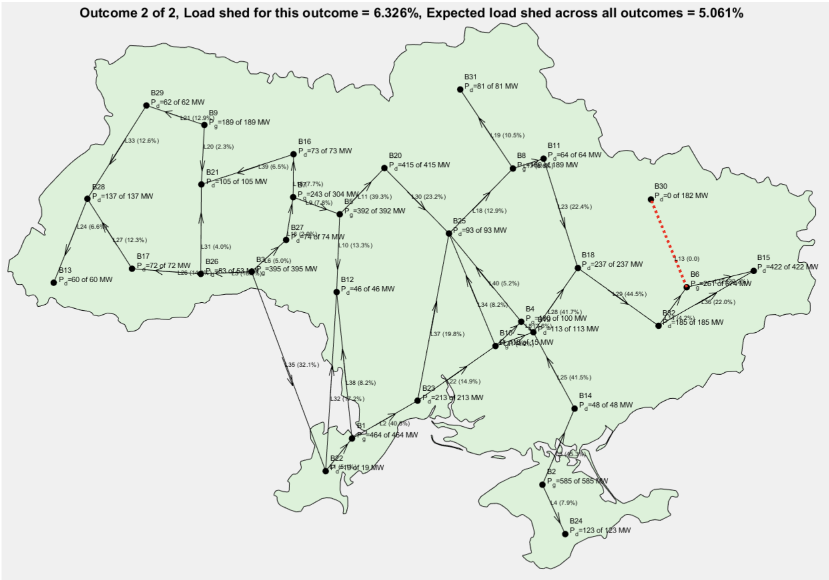

Figure 1: Line 13 is targeted in the case of one attack without any defense.

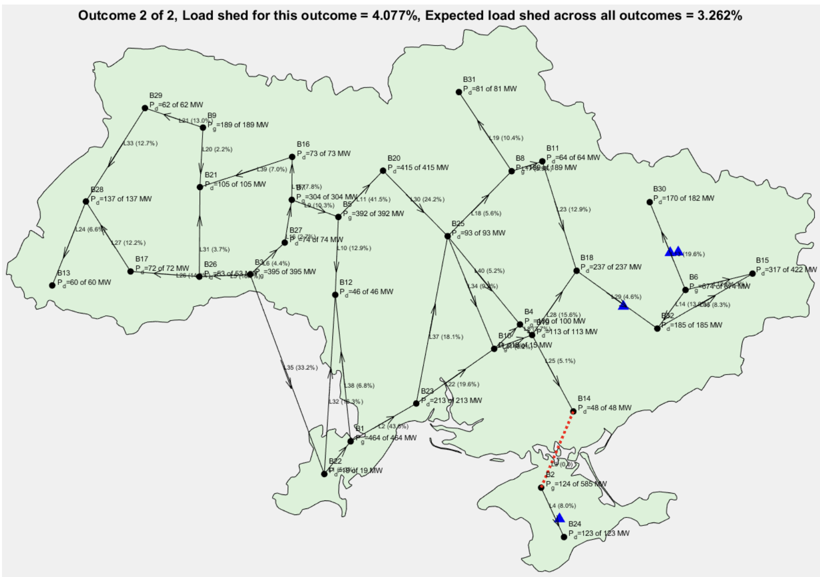

Figure 2: Line 3 is targeted in the case of one attack without maximum defense.

assumed that we had a viable method. We checked the attack locations for no defenses and any number of attacks and defend those locations, followed where they attack in response to our new defenses until the sum of our defense array is equal to four times the number of attacks. Our methodology largely follows these principles, but we ran into a few other important scenarios.

In situations where we provided a number of attacks greater than one the simulation can now plan a more complex strategy. We could see an example of the power of one defense to change the attack strategy. The figure below shows that when we defended line 2 and line 11 with four attacks available. The simulation targets lines 12, 14, 17 and 28. However, when we placed a defense at either Line 17 or Line 28 the attack strategy changes, as seen in figures 4 and 5.

From the result shown in figure 4 and 5, it is not necessarily beneficial to add defense location on both lines 17 and 28. In fact, doing so does not reduce the overall load shedding, as seen in figure 6.

Given this knowledge, we added to our methodology another rule. As we added defense locations to our array, we did so one at a time. We checked the load shedding for the defense of each target location and make the one that gives the best expected loadshedding across all scenarios a defense. In this way we added one defense at a time successively decreasing the load shedding until we reach the maximum number of defenses.

The issue this introduces is the simulation run time. For number of attacks fewer than four, the simulations took seconds, and it was easy to simulate defending each of the 1, 2, or 3, target locations until we had placed 4, 8, and 12 defenses. The issue escalated as we approached 4, 5 and 6 attacks and made it necessary to make

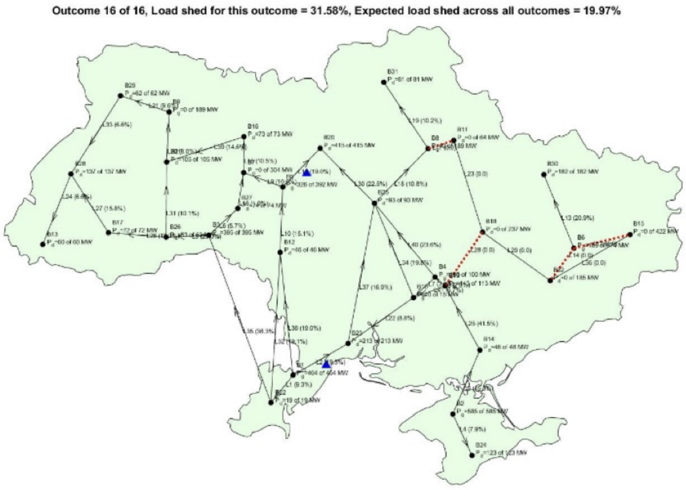

Figure 3: Lines 12, 14, 17 and 28 are targeted in the case of four attacks with two defenses.

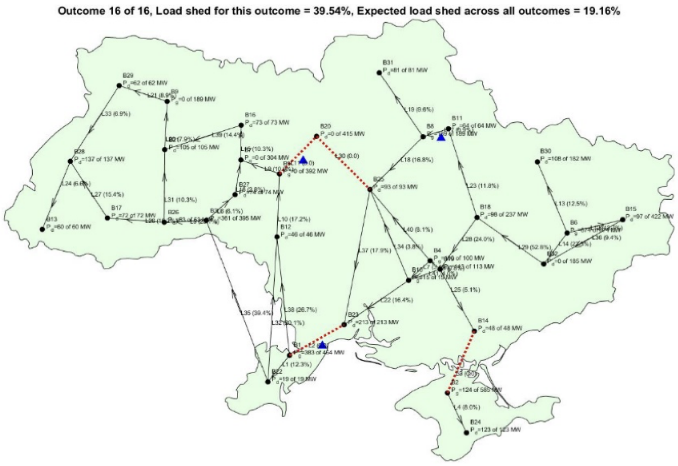

Figure 4: Lines 2, 3, 11 and 30 are targeted in the case of four attacks with three defenses.

some simplifying assumptions. We found that if we used the setup from the previous number of attacks it was a generally good reference for simulating the next highest number of attacks. We tested this by simulating the data for 3 attacks both from 0 defenses, and from 8 defenses determined from the data acquired by simulating two attacks. In each case our final 12 defense locations ended up very similar and had similar load shed values. We took this correlation forward to presume the same method for 5 and 6 attacks. For determining the defense locations for 5 attacks we started with the 16 defense locations determined from having 4 attacks simulated. We then followed our previous methodology of adding one additional defense location at each of the 5 targets individually to determine the 17th defense location. We followed this same process to 20 defense locations. If two locations had a tie in load shedding, we picked the location with a higher-powered generator.

When it came to simulating 6 attacks the simulation took about an hour and a half each time. Given this limitation we only simulated two scenarios and used our insight from previous simulations to determine our defense locations. We started with the scenario from 5 attacks and the 20 defense locations we had already chosen.

We then proceeded to choose 4 more defense locations. We chose lines 33, 19, 36, and an additional defense at line 11 which we had determined to be essential (Kyiv region). We noticed that line 11 carries 35.5% of the load. We simulated these new defense locations and found that they only slightly reduced the load shedding. It can be seen in the previous figures that line 35 also carries a large portion of the load, at 34.7%. We simulated the previously chosen 24 defenses and saw a reduced load shed, but we also saw line 35 targeted and failing. This is demonstrated on figure 8 shown below.

Given this additional information and the simulation run time constraint, we decided to defend the same locations chosen before but move our defense from Line 19 to Line 35. While Line 19 covers a distant northern

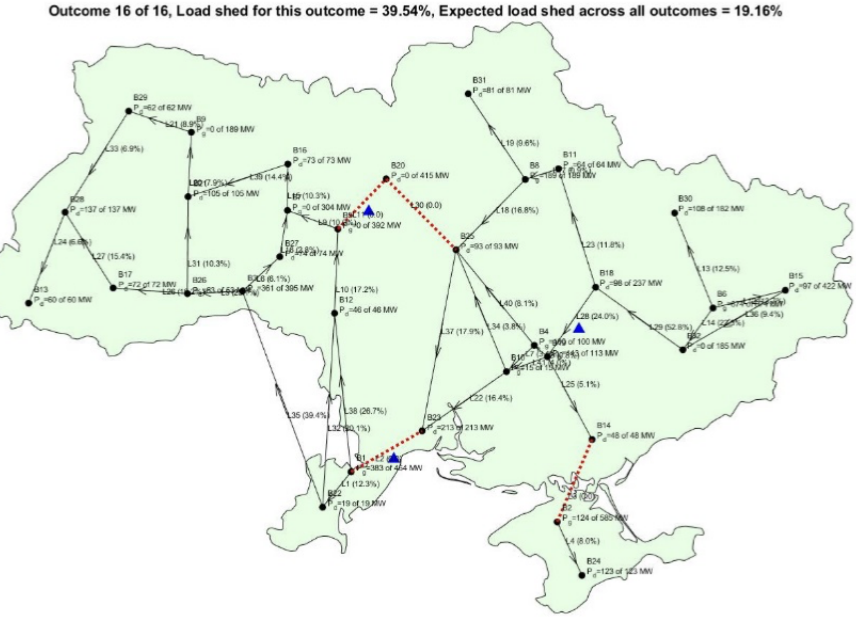

Figure 5: Lines 2, 3, 11 and 30 are targeted in the case of four attacks with three defenses.

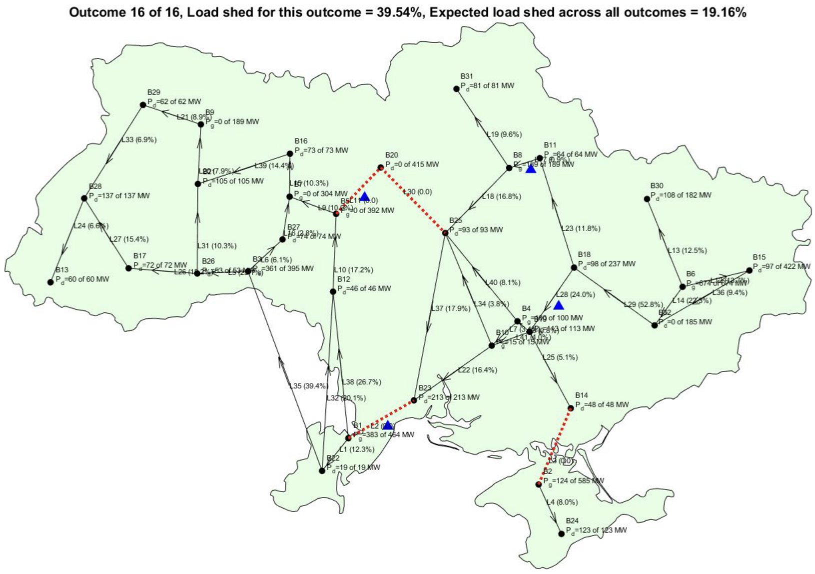

Figure 6: Lines 2, 3, 11 and 30 are still targeted in the case of four attacks with four defenses.

area it provides less load transfer for the system at roughly 10%. We chose to defend the same 20 locations as the 5-attack model and to defend Line 33, 35, and 36, and bolster line 11, while neglecting line 19. We anticipate the expected load shed overall to be reduced based on our previous simulations but didn't have another 80 minutes to confirm this information.

We followed the previously outlined method for each number of attacks except for 6. Simulating the load shed for every additional defense in every possible target location and only adding the single defense that gave the best expected load shed across all scenarios. We follow this procedure until we have defended 4 times the number of attacks. It is worth noting that we chose to optimize the expected load shed across all outcomes. In some scenarios the expected load shed across this particular outcome spikes, but the expected load shed across all outcomes still decreases. We determined that this was because in some scenarios the simulation still attacked a defended line that held the primary load; for example, our very important Line 11. If our defenses are maxed and they attack this load our expected load shed across all outcomes may be reduced. But in the worst-case outcome, meaning they penetrate that defense and hit the line we were trying to dissuade them from, we lose a

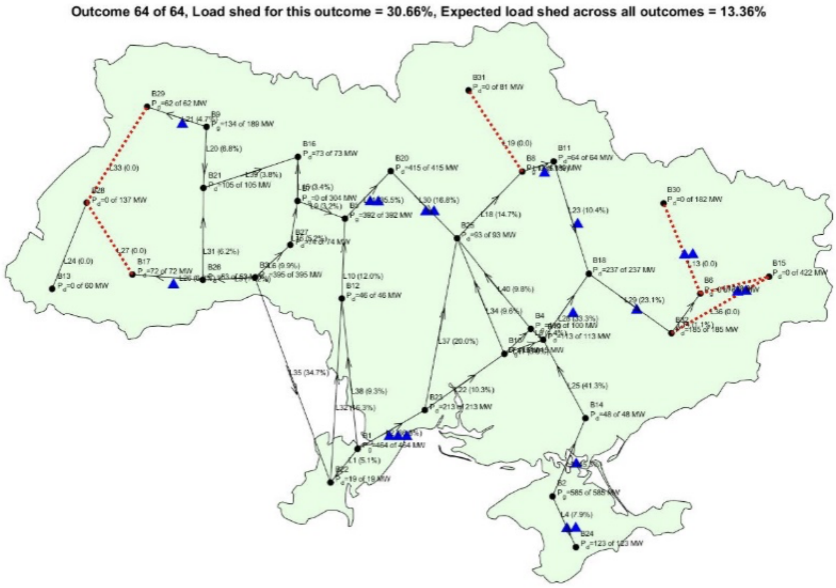

Figure 7: Lines 12, 13, 19, 27, 33, and 36 are targeted in the case of 6 attacks with 20 defenses.

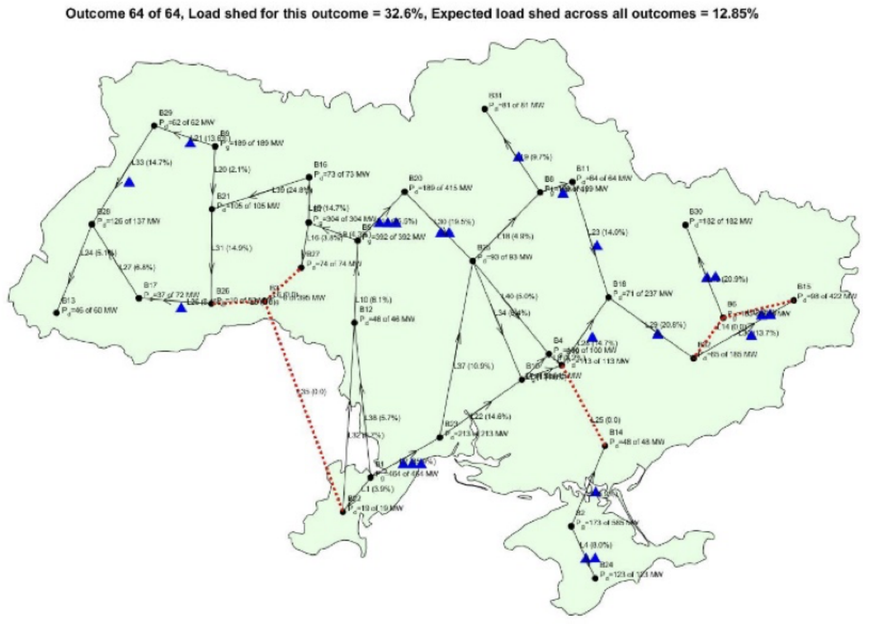

Figure 8: Lines 5, 6, 12, 14, 25, and 36 are targeted in the case of 6 attacks with 24 defenses.

lot of loads and have a large load shedding in this worst case. We use this information to advise emergency fuel and generators at the lines that are carrying the most load in order to mitigate any successful strikes despite best defenses. We chose to continue our methodology based on the expected load shed across all scenarios as we decided it was more statistically accurate to real events.

3 Analysis

3.1 One Attack

As discussed previously in the Defense Locations and Methodology section, the most vulnerable locations for each number of attacks are determined by running the simulation without any defenses set up. For the case of one attack, line 13 is targeted, as shown in the figure 9.

Contextually, this makes the most sense as line 13 situates in the easternmost part of Ukraine. This part

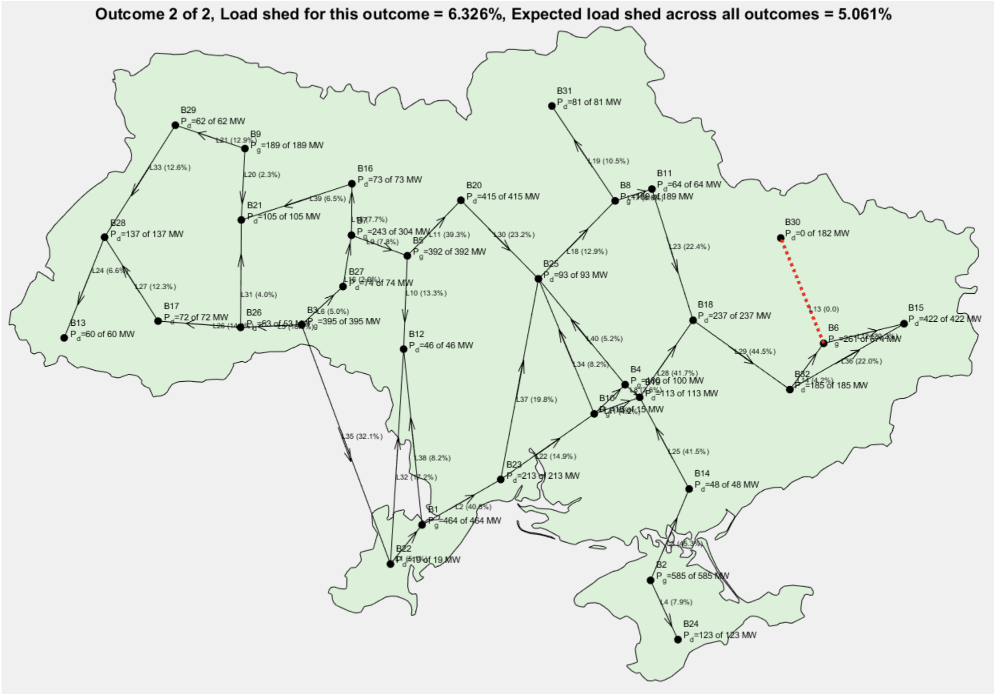

Figure 9: Line 13 is targeted in the case of 1 attack without any defense.

of the country is also known as the Donbas region, a place that has seen constant territorial conflicts between Russia and Ukraine [2]. Cutting power supply to this region will further weaken the Ukrainian defense effort and thus, will strengthen Russian advancement. For this scenario, placing three defenses in the Donbas region (two on line 13 and one on line 29) will shift the attack onto line 3, where the fourth and final defense is placed on the adjacent line 4. This defense configuration results in the best load shedding value, as shown in figure 10.

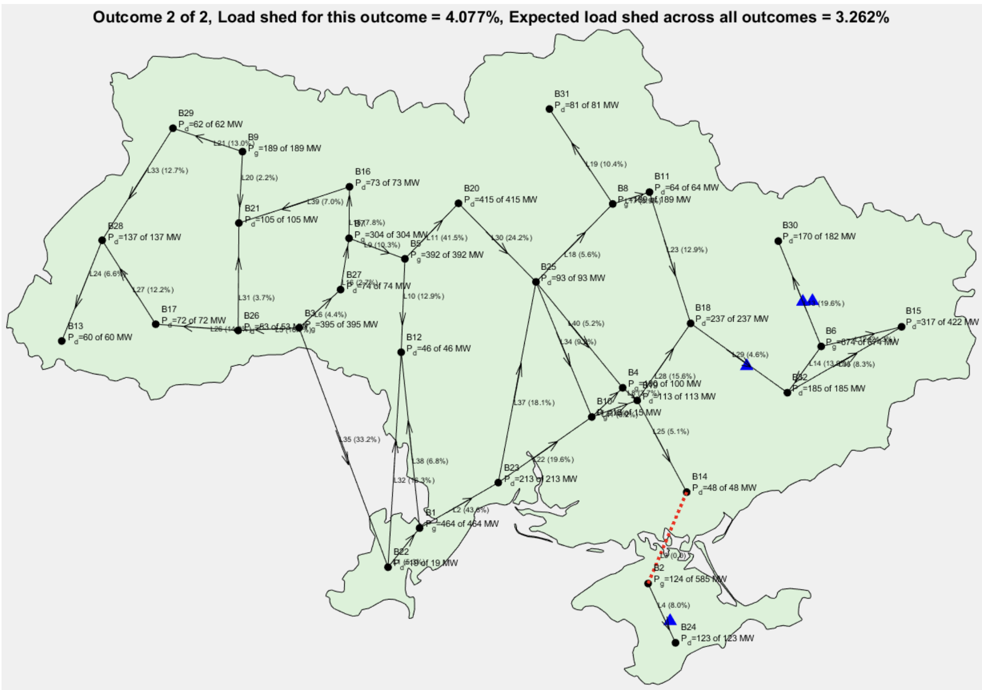

Figure 10: Line 3 is targeted in the case of 1 attack with 4 defenses. Defenses located at lines 4, 29 (1) and 13(2).

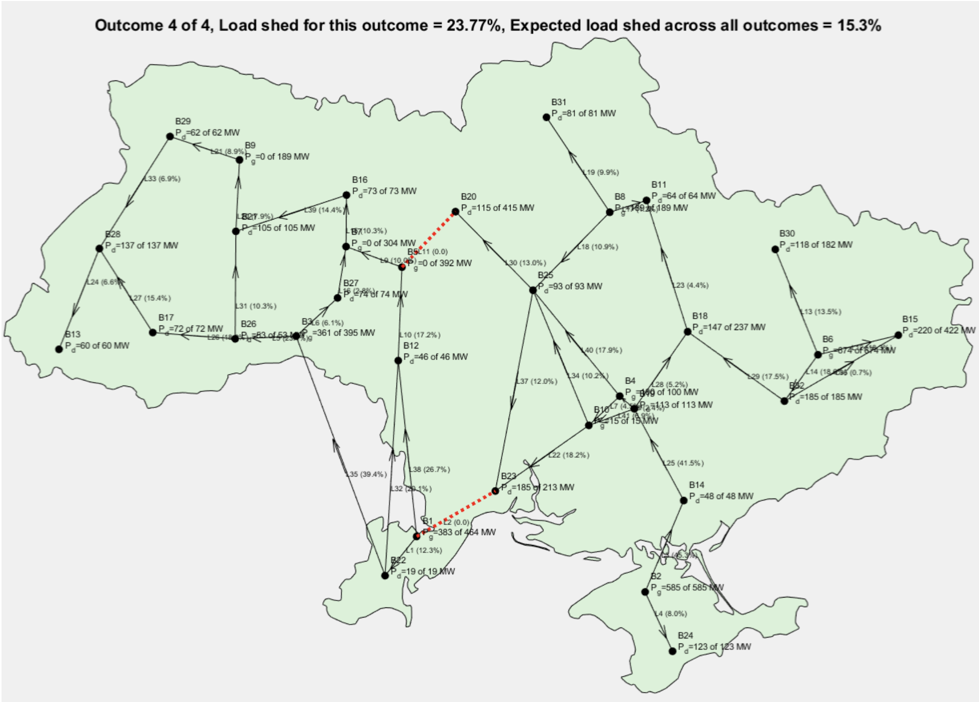

Figure 11: Line 11 and 2 are targeted in the case of 2 attacks without any defenses.

3.2 Two Attacks

Increasing the number of attacks to two, the result becomes different. For the case of two attacks without any defenses, both line 11 and line 2 are targeted, as shown in figure 11.

Contextually, this makes the most sense as line 11 situates in the Kyiv region of Ukraine whereas line 2 situates in the Odessa region of the country. Kyiv is one of, if not the most important region as the Ukraine since the capitol city is here. Odessa, on the other hand, is equally as crucial since the largest and only deep-water port in Ukraine is located in this region [7]. Cutting power supply to Kyiv will send Ukraine's most populous region, which is also the economic and political center of the country, into chaos. Likewise, doing the same to the Odessa region will allow Russian forces to gain easier access to the port of Odessa, making it a viable Russian deployment spot. Nullifying line 11 and line 2 will also cut off the East-West connection of the grid, further increasing the load shedding value. For this scenario, placing the defenses as shown in figure 12 results in the best load shedding value.

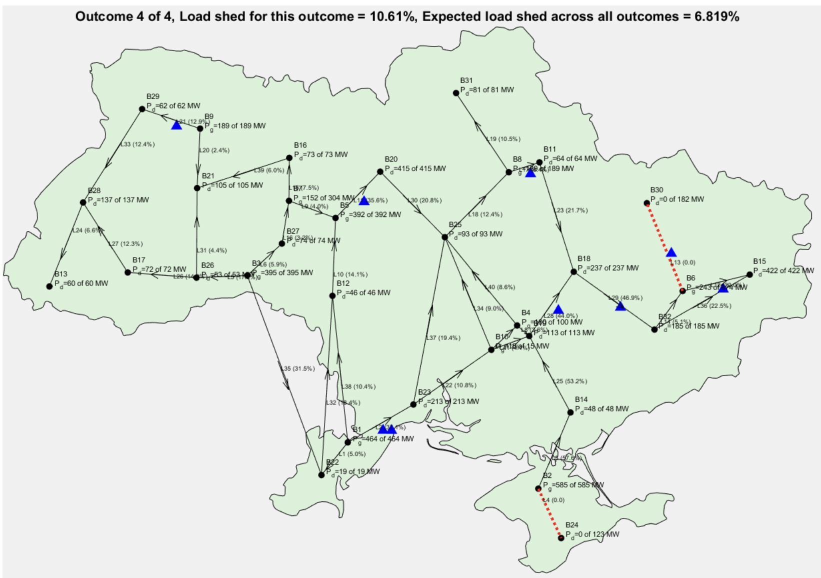

Figure 12: Line 13 and 4 are targeted in the case of 2 attacks with 8 defenses. Defenses located at lines 11, 12, 13, 17, 19, 21, 28 (1) and line 2(2).

The reason why this defense configuration yields the best load shedding value is because the two crucial regions of Kyiv and Odessa are well protected from any attacks. Furthermore, the East-West connection of the grid is also preserved, there by solidifying its interconnectedness and interdependency.

3.3 Three Attacks

Increasing the number of attacks to three without any defenses, the result again changes. Line 3, on top of line 11 and line 2, are targeted as shown in figure 13 below.

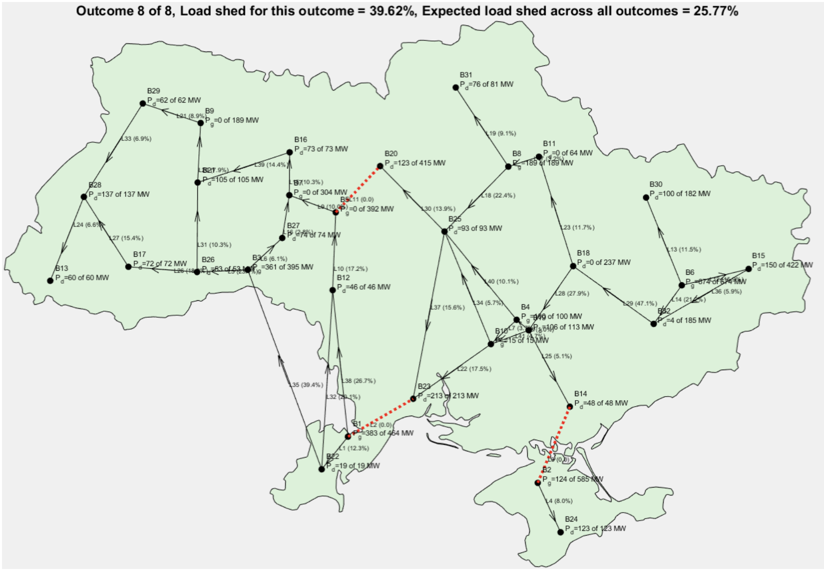

Figure 13: Line 2, line 3 and line 11 are targeted in the case of 3 attacks with no defenses.

Contextually, the reason why line 2 and line 11 are targeted have been discussed above. For line 3, it serves a very important role of connecting the Crimea region of Ukraine with the main power grid. Crimea is a peninsula that was annexed by Russia in February 2014, for reasons such as the local population's ethnic ties with Russia and the presence of port Sevastopol, the only deep-water port on Russia's Black Sea littoral [6]. Cutting off power to Crimea will slow down Ukrainian advancement into the region. For this scenario, placing the defenses as shown in figure 14 results in the best load shedding value.

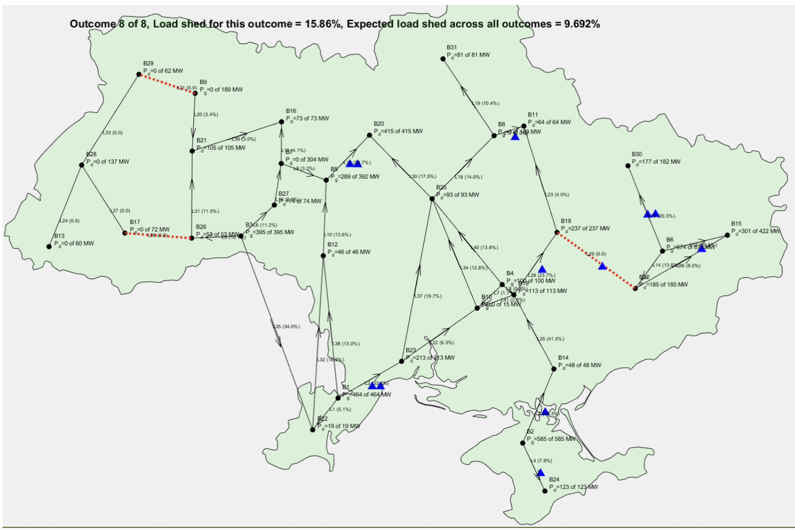

Figure 14: Line 21, line 26 and 29 are targeted in the case of 3 attacks with 12 defenses. Defenses placed at lines 3, 4, 12, 23, 28, 29 (1) and lines 2, 11, 13 (2).

The reason why this defense configuration yields the best load shedding value is because the two crucial regions of Kyiv and Odessa are well protected from any attacks, as well as the Crimea region. With Kyiv and Odessa protected, the East-West connection of the grid is also preserved, there by solidifying its interconnectedness and interdependency. This defense configuration would result in attacks on the Donbas area (line 29) and the westernmost part of Ukraine (line 21 and line 26). Although strategically, these locations are not as important as others, they are the most populous regions within Ukraine, as shown in figure 15. A direct attack on these regions will certainly stretch out Ukraine's effort and resources, thus making it easier for subsequent attacks on other key locations.

Figure 15: Population density of Ukraine by regions [3].

3.4 Four Attacks

Increasing the number of attacks to four without any defenses, the result is very similar to the case of three attacks but with a slight change. Line 4, on top of line 3, line 11 and line 2, are targeted as shown in figure 16 below.

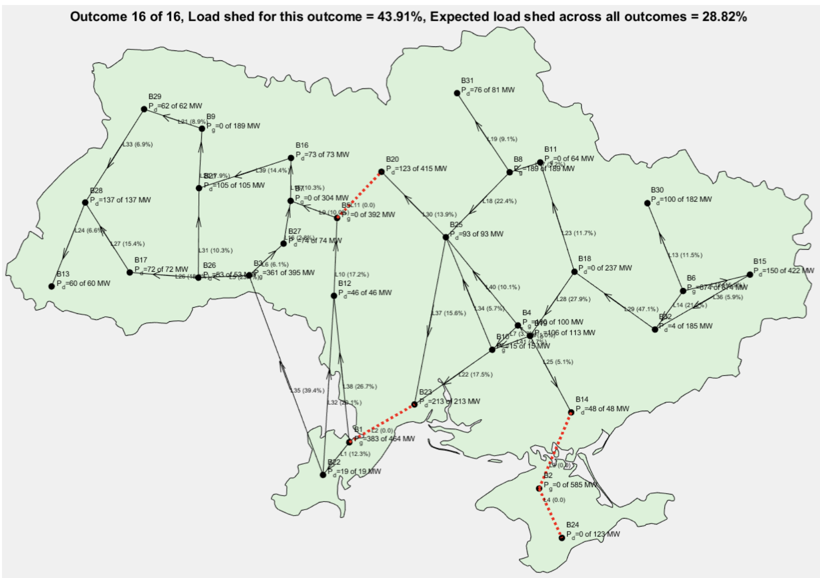

Figure 16: Line 2, line 3, line 4 and line 11 are targeted in the case of 4 attacks with no defenses.

Contextually, the reason why line 2, line 3 and line 11 are targeted have been discussed above. Line 4 is targeted in this case because of the same reason as line 3: close proximity to Crimea. For this scenario, placing the defenses as shown in 17 results in the best load shedding value.

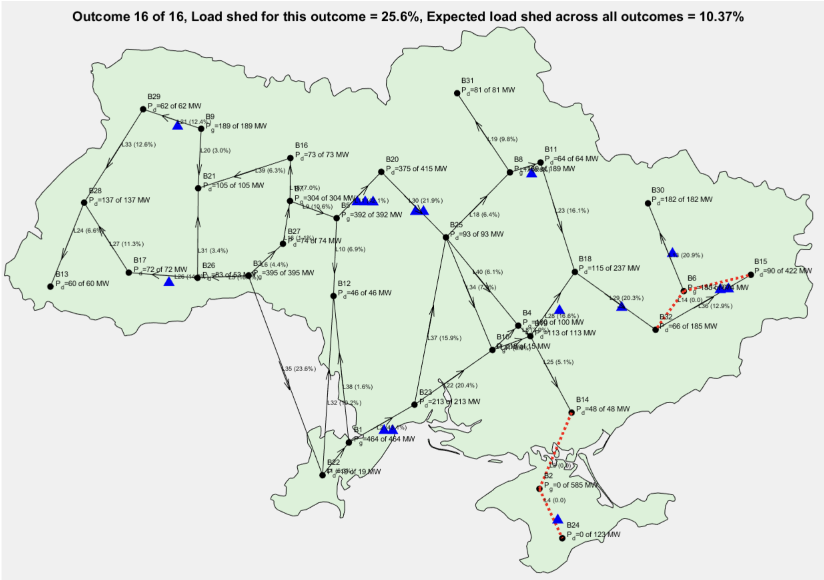

Figure 17: Line 3, line 4, line 12 and line 14 are targeted in the case of 4 attacks with 16 defenses. Defenses are place at lines 4, 13, 17, 21, 26, 28, 29 (1), lines 2, 12, 30 (2) and line 11 (3).

The reason why this defense configuration yields the best load shedding value is because the two crucial regions of Kyiv and Odessa are well protected from any attacks, as well as the densely populated westernmost regions of Ukraine. As discussed previously, the fact that Kyiv and Odessa are protected means that the East-West connection of the grid is also preserved. With this defense configurations, Ukraine can allocate resources to be close to the Southeastern part of the country, thus any recovery and aid efforts can be carried out efficiently for both targeted regions.

3.5 Five Attacks

Increasing the number of attacks to five without any defenses, the result is very similar to the case of three attacks but with a slight change. Line 21 and line 26, on top of line 3, line 11 and line 2, are targeted as shown in figure 18.

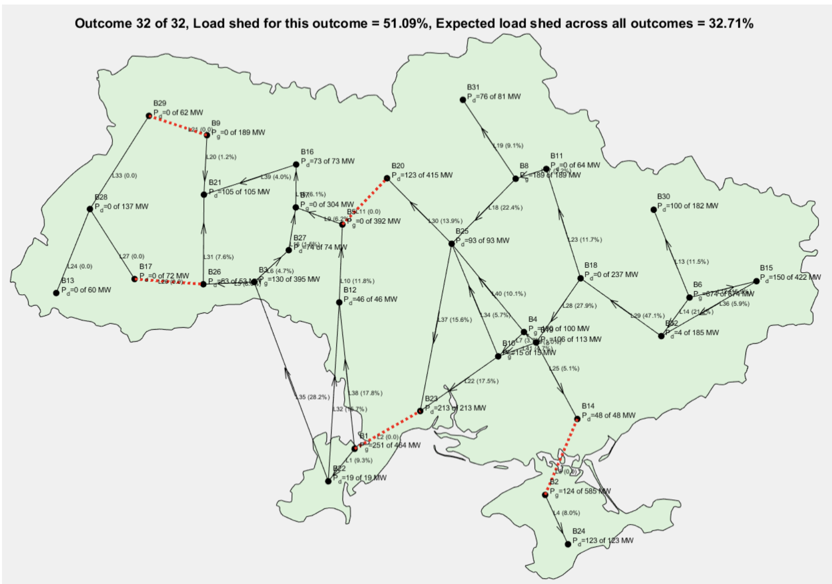

Figure 18: Line 2, line 3, line 4 and line 11 are targeted in the case of 5 attacks with no defenses.

Contextually, the reason why line 2, line 3 and line 11 are targeted have been discussed above. Line 21 and line 26 are targeted in this case because of their location in the densely populated westernmost parts of Ukraine. For this scenario, placing the defenses as shown in figure 19 results in the best load shedding value.

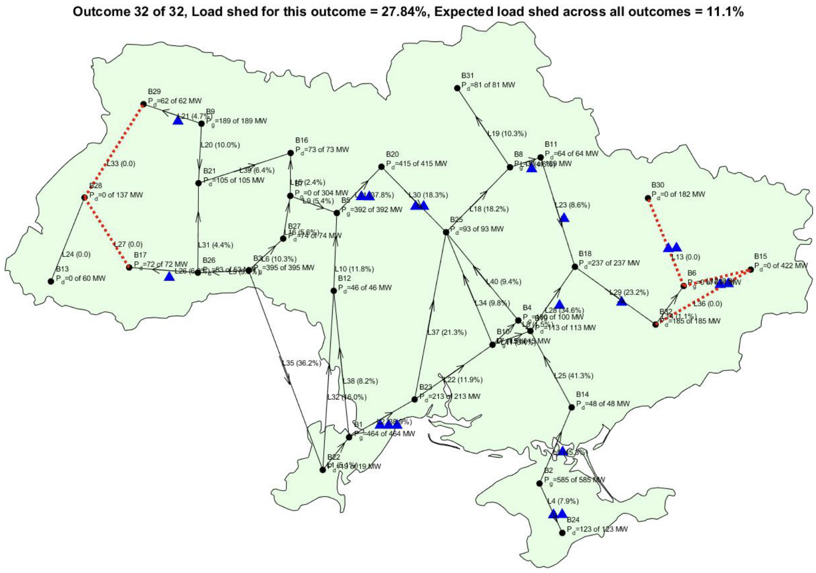

Figure 19: Line 12, line 13, line 27, line 33 and line 36 are targeted in the case of 5 attacks with 20 defenses. Defenses are placed at lines 3, 17, 21, 23, 26, 28, 29 (1), lines 4, 11, 12, 13, 30 (2) and line 2 (3).

The reason why this defense configuration yields the best load shedding value is because the three crucial regions of Kyiv, Odessa and Crimea are well protected from any attacks. Interestingly, the Donbas region is still targeted (line 13 and line 36) despite each line having two defenses set up. Out in the westernmost part of the country, having a defense set up on each of line 21 and line 26 further pushes the attack targets westwards, onto line 33 and line 27. This is viewed as beneficial for Ukraine as the targeted lines are further away from densely populated areas. Contextually, pushing the targeted attacks further westwards will force Russia into a tougher situation with less room for error. This is because a misguided or inaccurate attack across the Polish border could trigger conflicts between Russia and Poland, which is a NATO member [8].

3.6 Six Attacks

Increasing the number of attacks to four without any defenses, the result is comprehensive of the previous cases. Line 2, line 3, line 4, line 11, line 21 and line 26 are targeted as shown in figure 10.

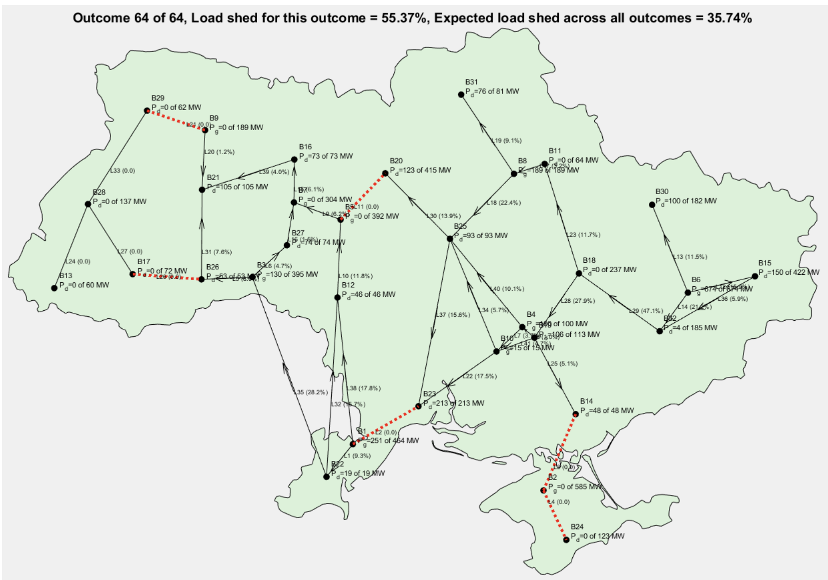

Figure 20: Line 2, line 3, line 4, line 11, line 21 and line 26 are targeted in the case of 6 attacks with no defenses.

Contextually, the reason why line 2, line 3, line 4, line 11, line 21 and line 26 are targeted have been discussed above. Disrupting the lives of millions of Ukrainian in these parts of the country will heavily deplete Ukrainian effort and resources, thus opening up possibilities for attacks in other key areas, such as the easternmost part of the country.

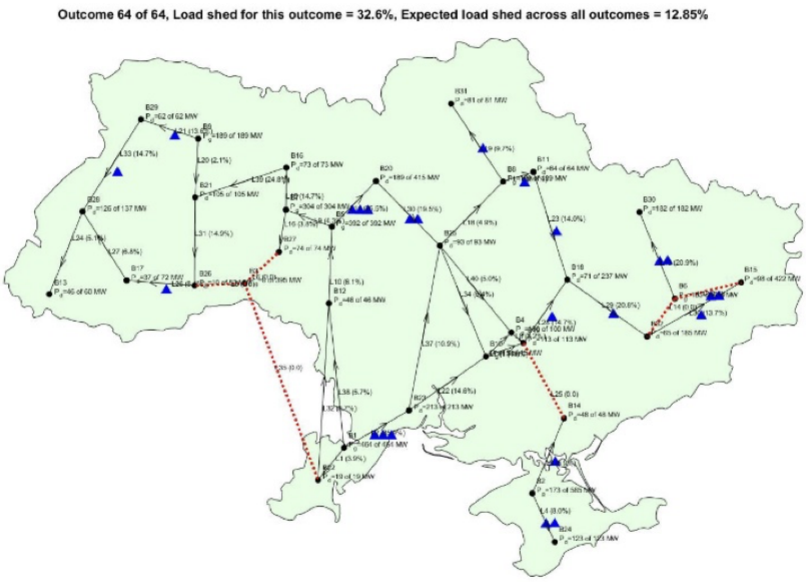

Figure 21: Lines 5, 6, 12, 14, 25, and 36 are targeted in the case of 6 attacks with 24 defenses. Defenses are placed at lines 3, 17, 19, 21, 23, 26, 28, 29, 33, 36(1), lines 4, 12, 13, 30 (2) and lines 2, 11 (3).

After seeing the result of this simulation and running into time constraints we decided to establish our final locations for 6 attacks as placed at lines 3, 17, 19, 21, 23, 26, 28, 29, 33, 35, 36(1), lines 4, 12, 13, 30 (2) and lines 2, 11 (3) for 24 defenses. We removed line 19 and defended line 35. This is because we saw that the power generated at Pg B3 is 395 MW vs the 81 MW Pd at B31. We made the decision to risk losing this power distribution in exchange for protecting the large generator at B3. We assume that this would greatly improve our overall load shedding figure.

4 Limitations

The method of defense mentioned in this report is mostly concerned with the expected load shed across all outcomes, rather than the load shed of a particular outcome. As such, there are some scenarios where a line is targeted despite having at least a defense set up at that line already. For example, in figure 4, line 13 is still targeted despite having a defense set up there already. The same thing could be said about figure 6, line 29. For these outlying cases, it is recommended that the Ukrainian side stockpile extra fuel and other necessities at these key locations, since they might lose power during a worst-case attack, despite the overall outcomes being the best.

Another limitation of the method mentioned in this report is that the simulation does not automatically run through every attack case. In fact, the number of attacks and defense locations are adjusted manually after each run. Not only does this create a bottleneck in terms of runtime, but there is also a possibility that an automatic simulation will yield better solutions that are omitted when simulating manually at high number of attacks.

An additional limitation is introduced from the design of the system model. When simulating with four or more attacks, the runtime for the simulation drastically increases. For 5 attacks the results take about 80 seconds on a home PC. Results for 6 attacks took 4812 seconds or about 80 minutes for one simulation. This means that to make a defense decision for six attacks, previous results of simulation with fewer attacks must be used. Based on those previous results, defense scenarios are tested one by one to get the optimal loadshedding value and displayOutcome image.

5 Conclusion

In conclusion, we can see that the defense goals shift as the number of attacks increases. We see that with one attack they focus on the eastern front and the southern peninsula containing Crimea. In context this makes sense as they can only hit one target, they would weaken the eastern frontline or weaken the capital where they can make an entry by sea through an area, they are familiar with in Crimea. As the number of attacks increases, we see the attack pattern shifts. With two attacks the targets become the center lines, with the goal of separating the eastern and western fronts. As more attacks are added, Crimea and the eastern front (Donbas region) are brought back into focus. With three attacks, the western front becomes involved as well. A common trend emerges, showing that the simulation prefers 3 primary attacking goals, each enacted when additional resources come into play. First, line 2 and 11 connecting the eastern and western fronts are highly targeted. As defensive patterns adjust, subsequent attacks consistently come back to attacking these lines even when they are defended. The next goal of the simulation when attacking is to destroy the power supply to Crimea and Odessa. Logistically this makes sense as it is a contentious territory and allows a secluded entry point by sea if controlled. As more resources become available disconnecting the western front also becomes important. We can see this trend repeated in figure 14 and figure 18. As we defend the targeted central region the focus shifts to the western front and eastern fronts.

On a side note, leaders of the Ukrainian defense should keep large power generators such as B1, B2, B3, B5, B6, on top of their transmission lines well protected. We recommend having emergency resupply resources in these locations in case an attack is successful. The reason for this is the loadshedding value can spike up as high as 40-50% when attacks are successful. Additionally, secondary targets seem to include more powerful distribution stations, especially Pd B15, B20, B24, B28, B30, B31, and B32. This is a logical conclusion as we must protect important areas to get energy distributed.

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