Optimizing Electricity Distribution in Energy-Poor Regions: A Graph Theory and MDP Framework for Cuba

By: Lisa Zheng

Abstract

In this paper, different algorithms in increasing consideration of uncertainty (Dijkstra's, Ford-Fulkerson, Markov Decision Processes, and Q-Learning) are used to simulate Cuba's electricity grid, taking into consideration fuel shortages and wind variability for the goal of optimizing its energy flow. The capital of Cuba, Havana, requires a minimum of 3000 MW of energy for its citizens, but the island's energy grid can only generate 1935 MW on average. This is primarily due to obsolete equipment and poor maintenance. However, when these computer frameworks are implemented, an estimated average 2700-2900 MW of energy is possible. Specifically, Dijkstra's results in 2325.25 MW, Ford-Fulkerson in 2800.00 MW, Markov Decision Process in (extrapolated) 3198.38 MW, and Q-Learning in 2739.31 MW. These results show a major potential improvement of at least 1000 MW in Cuba's energy generation if a similar application is implemented to make the most optimal decision based on the rewards system. A potential impact is the installation of monitoring devices in the power plants that detect fuel shortages and transmission failures and send back information as to which action to take next: reroute, do nothing, or take a load off. This solution to Cuba's energy problem is significantly more affordable than currently existing plans at tapping into renewable energy or completely re-structuring the grid. Additionally, it addresses the issue from its roots instead of various bottom-up approaches.

Problem

Importance

Cuba's electricity system is obsolete and in urgent need of repair. Daily blackouts lasting 18 hours or more are common and destroy the country's economy. On an average day, the Cuban national government can only meet 50-70 percent of the country's needs. The National Electric System, built after 1959, has not received consistent maintenance for 35 years, leading to the collapsing state of the grid today. According to Cuba's Unión Eléctrica (UNE), less than 50% of the sector's total thermoelectric is operational. Schools are forced to close, non-official workers forced to stay home. Refrigerators lose their cooling power, leading to rotten food. Students are unable to study due to closed schools. Businesses lose revenue. Internet connectivity is less reliable. Oil-based power plants have suffered an energy crisis due to dwindling imports from Mexico, Russia, and Venezuela. Additionally, in October 2024, Hurricane Oscar hit Baracoa, an eastern city where much of the electric infrastructure is concentrated. In November 2024, Hurricane

Rafael hit the island, destroying the power grid along with infrastructure. Cubans also face food and medicine shortages in addition to gas and power shortages, causing an exodus leaving the country. 10%, or 1 million people, left Cuba between 2022 and 2023 (10,055,968 in December 2023 from 11,181,595 in December 2021), the largest migration in the country's history. This downward trend has continued, and Cuba's current estimated population is 8.62 million. Almost 645,000 sought asylum through the United State's southern border. The main thermoelectric generators are 50 years old and have a lifetime of only 25-30 years. The United States' trade embargo with Cuba has limited investment for its power plants as well as access to repairment parts. Violent protests have emerged around the island, although the lack of Internet has prevented their reports. Specifically, the main power plant, Antonio Guiteras, continuously broke down. After recovering from long stretches with no power, the immediate usage has caused further strain on the Cuban electricity system. The Cuban government warned that it may have to further increase gas and electricity prices to encourage its citizens to cut back on energy usage. Currently, it is employing a rotation system to decide which provinces receive the blackouts, but it is inconsistent and a lack of homogeneity, causing dissatisfaction.

Neglectedness

Cuba on an average day can only meet 50-70% of its energy demand. In the first six months of 2025, its grid collapsed four times. The National Electric System, built after 1959, has not received the investment and maintenance for 35 years. Healthy grids should be able to detect common issues like transmission line failures and generator trips, but Cuba's old system cannot detect them. Antonio Guiteras, the biggest of the crude oil and fuel oil power plants, breaks down frequently due to the lack of repair parts. Cuba's power plants also suffer because 85% of the plants heavily rely on poor-quality crude oil that is corrosive due to its high amount of sulfur, exacerbating the deterioration of boilers, turbines, and pipes. Though Cuba has a wealth of renewable energy resources such as wind, solar, and sugarcane biomass, there has not been adequate funding to implement them fully. The neglectedness stems primarily from Cuba's government, which focuses on building new hotels and boosting its tourism industry. According to Cuba's National Statistics Office, from 2010 to 2024, the country spent 32% of its total investment on tourism infrastructure and only 12% on energy infrastructure. Politically, the United States denies the consequences of its embargo with Cuba, which many officials agree upon is the main reason for the lack of international support. Many countries are deterred by Cuba's hesitation to abandon its inefficient economic model and take on market incentives that attract investment and growth.

Inefficiencies of Status Quo

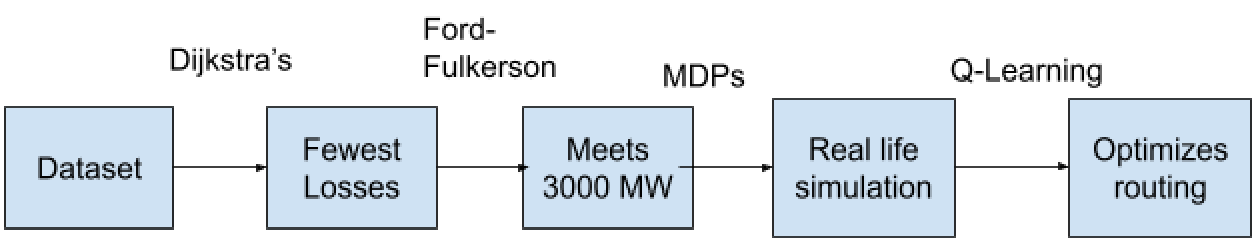
Small solar parks are being built and the solar capacity reached 298 MW by the end of 2024. However, these innovations are extremely slow. According to the Electric Union (UNE) report on April 1, 2025, photovoltaic sites generated 873 MWh, or a continuous 36 MW, which is insufficient to meet citizens' instantaneous demands. Though the Cuban government projected a goal of getting 37% of its energy sources from renewable sources by 2030, it has only reached 3% in 2025. Cuba is talking with international investors and partners, such as Russia (modernizing its existing thermal facilities), China (building up to 2000 MW of solar power with more than 92 solar parks across the country), and Mexico and others (for fuel supplies). China is its most beneficial partner. After commissioning the "Hoyo Colorado" Solar Park in Martí, the solar power collectively generated 400 MW, surpassing the large Antonio Guiteras. This advancement would reduce the reliance on diesel, create new occupations, and reduce carbon emissions. However, despite 16 photovoltaic cells delivering 1542 MWh with a maximum capacity of 440 MW, the system availability is still not enough to meet the demand. In peak evening hours, for example, the projected generation would be 2000 MW whereas the demand is 3500 MW. Another example is La Sabana park in Bayamo, which operates up to 24 MW capacity, or 20% of Granma's demand. A single solar park is not enough to solve Cuba's energy deficit, especially as it is connected to the National Electric System (SEN) and requires synchronization with the national grid. Some citizens have even noted that the situation has gotten worse since the 8 solar parks have been installed. In general, the parks only deliver 70-75% of their capacity due to cloud coverage, introducing variability contrasted to thermal plants' stability.

There are also plans to rehabilitate thermal plants (Felton 2, Mariel 7, Nuevitas 4, and Renté 4 blocks) and re-incorporate 550 MW through boiler and water maintenance. However, the structural failures prevent these plans from operating reliably. Another crucial resource is substituting conventional fuel with LNG (liquefied natural gas), which has lower sulfur content (<10 ppm) and 40-50% less CO_2 emissions than coal.

Using sugarcane biomass is another viability. However, the reduction in its availability (3 million tons of crude, or 60,000 barrels per day, in 1990 to only a quarter of that quantity in 2021) is one of the main reasons why bioelectric plants, like the one near the Ciro Redondo plant, do not receive much investment attention.

Many businesses and hospitals are installing generators, but these are only affordable by the wealthy and are not scalable. Though Venezuela donates fuels, Minister O Levy states that it is not enough to support the energy demand in the country. According to energy fellow Jorge Piñon, the only solution is a total recapitalization of the base load, distributed generation, and renewable energy matrix, which would cost $8 to 10 billion dollars of investments.

Methodology

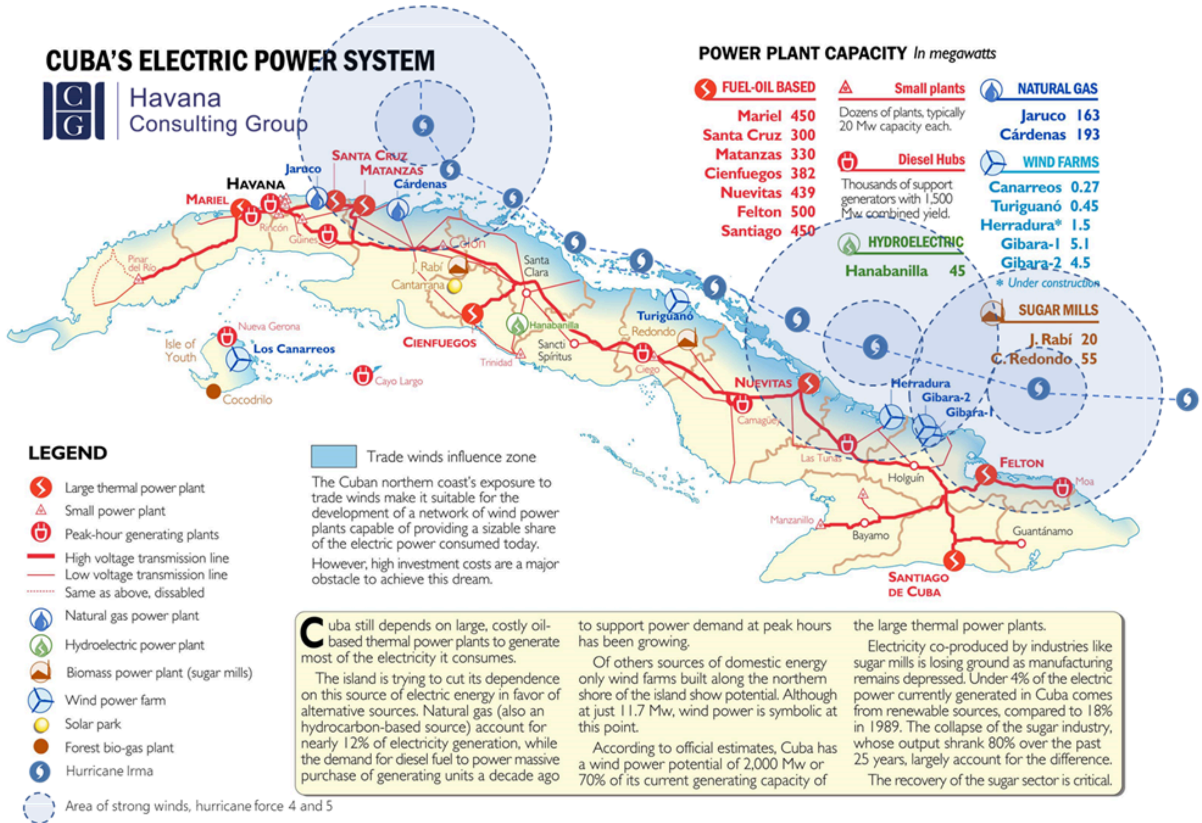


Tools Needed:

- **Modeling and Simulation**:
  - **PyTorch Geometric (PyG) Graph Neural Network:** For graph modeling and algorithms (Maximum Flow, Dijkstra's).
  - **NetworkX**
  - **MATLAB or PowerFactory**: For grid validation and synthetic data generation.
- **Visualization and Interface**:
  - **Gephi or Dash (Python)**: To visualize graphs and create operator interfaces.
- **Deployment and Testing**:

- **Docker**: To package models into a deployable toolkit.
- **OpenSCADA**: To simulate integration with grid control systems.

Dataset



Fuel power plant	Power Plant capacity
EG Mariel power station	450
Termoeléctrica de Santa Cruz del Norte	300
Antonio Guiteras Thermoelectric power plant	330
Cienfuegos	382
Nuevitas	439
Felton	500
Santiago	450

Natural gas	
Jaruco	163
Cardenas	193
Wind farms	
Canarreos	0.27
Turiguano	0.45
Herradura	1.5
Gibara-1	5.1
Gibara-2	4.5
Sugar Mills	
J. Rabi	20
C. Redondo	55
Hydroelectric	
Hanabanilla dam	45

Dijkstra's Algorithm

Dijkstra's algorithm uses a min-priority queue and iterative processes to find the shortest path through a weighted, undirected graph from a source node to all other nodes. Its most popular application is in GPS routing, delivery vehicles, network routing, and pathfinding in robotics. Essentially, the code is as follows.

1. Set dist[source] = 0 and all other edges to be infinity.
2. Push this into the min heap as a pair <distance, node> (<0, source>)
3. Pop the topmost element (the node with the smallest distance).
    a. For each adjacent neighbor v of this element:
    b. Dist[v] = dist[u] + weight[u][v]
    c. If this new distance is greater than the current dist[v], update it.

   d. Push the updated pair <dist[v], v> into the heap
4. Repeat step 3 until there are no more nodes
5. Return the distance array, which contains the shortest distance from the source to all other nodes.

When applied to Cuba's grid, we seek to minimize the energy loss when traveling so that the maximum amount of power can be delivered from one plant to another.

Ford-Fulkerson

While Dijkstra's considers individual capacities, Ford-Fulkerson considers the maximum total flow from all power plants to the Havana Load.
Ford-Fulkerson or the maximum flow algorithm starts with the initial flow at 0.

1. While there is an augmenting path from the source to the sink:
   a. Find an augmenting path using any path-finding algorithm (DFS or BFS)
   b. Determine the amount of flow that can be sent along the augmenting path, which is the minimum residual capacity
   c. Increase flow along the augmenting path by this determined amount.
2. Return the maximum flow.

Here, we set an average transmission loss of 15%, approximating Cuba's 15.29% from World Bank data.

Markov Decision Processes (MDPs)

The agent travels through a markov chain where each action has a specific probability and receives rewards (positive for a desired action and negative for an undesirable action) until the game terminates.

As a simple example, a squirrel could be traveling on a 3x3 grid where getting acorns would indicate +5 in rewards and encountering a hawk would indicate -10 in rewards and would terminate the game.

These satisfy the Markovian property in that if we know the present state, the past state does not tell us any information about the future. It's 'memoryless' in the sense that the state s' at time t+1 depends only on the previous state s and action a.

Bellman Equation:

$$V(s) = max_a(R(s,a) + \gamma V(s'))$$

MDPs are used to handle uncertainty, such as grid failure, fuel shortage, or wind variability for wind farms.

Q-Learning

Q-learning is a kind of reinforcement learning.

$$Q(S,A) \leftarrow Q(S,A) + \alpha(R + \gamma Q(S',A') - Q(S,A))$$

Q-value: the expected reward by taking an action in a specific state, updated over time using the Temporal Difference (TD) update rule.

- S is the current state
- A is the action taken by the agent
- S' is the next state
- A' is the best next action in S'
- R is the reward for taking action A in state S
- γ: discount factor, to prevent infinite rewards
- ɑ is the learning determining how much past Q-values affect new Q-values.

Bellman equation in Q-learning:

$$Q(s,a) = R(s,a) + \gamma max_a Q(s',a)$$

- Q(s, a) represents the Q-value at state s when taking action a
- R(s, a) represents the immediate reward at state s when taking action a
- γ: discount factor, to prevent infinite rewards
- $max_a Q(s',a)$ is the maximum Q-value for the next state s' and all possible actions.

ε-greedy exploitation v. exploration.

- With 1-ε probability, the agent picks the action with the highest Q-value. This is exploitation because the agent is acting off of their existing knowledge
- With probability, the agent picks a random action to see if there are potentially better ways to earn awards. With this, the agent can discover new strategies and improve over time.

A Q-table informs the agent of which actions lead to better rewards. Its values are updated as the computer is trained. The higher the Q-value is, the greater the reward. Rows represent the states and the columns represent the possible actions. Epochs are the number of times it will be trained.

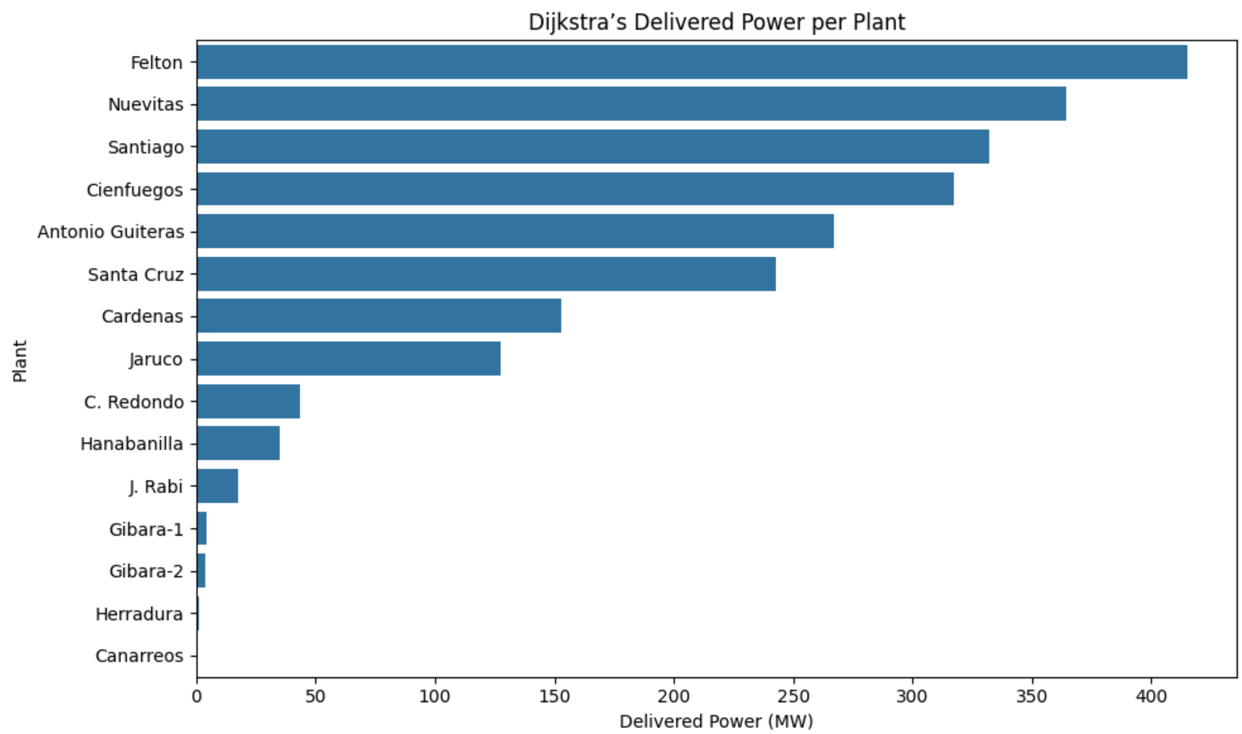
Results

Dijkstra's Algorithm:

Plant	**Path**	**Total Loss (%)**	**Delivered Power (MW)**
Santa Cruz	[Santa Cruz, Substation1, Havana_Load]	19.0	243.0000
Antonio Guiteras	[Antonio Guiteras, Substation 1, Havana_Load]	19.0	267.3000
Cienfuegos	[Cienfuegos, Substation2, Havana_Load]	17.0	317.0600
Nuevitas	[Nuevitas, Substation2, Havana_Load]	17.0	364.3700
Felton	[Felton, Substation2, Havana_Load]	17.0	415.0000
Santiago	[Santiago, Substation2, Havana_Load]	17.0	332.0000

Jaruco	[Jaruco, Substation1, Havana_Load]	15.0	127.5000
Cardenas	[Cardenas, Substation2, Havana_Load]	15.0	153.0000
Canarreos	[Canarreos, Substation1, Havana_Load]	12.0	0.2376
Herradura	[Herradura, Substation1, Havana_Load]	12.0	1.3200
Gibara-1	[Gibara-1, Substation2, Havana_Load]	12/0	4.4000
Gibara-2	[Gibara-2, Substation2, Havana_Load]	12.0	3.9600
J. Rabi	[J. Rabi, Substation1, Havana_Load]	13.0	17.4000
C. Redondo	[C. Redondo, Substation2, Havana_Load]	13.0	43.5000
Hanabanilla	[Hanabanilla, Substation2, Havana_Load]	12.0	35.2000

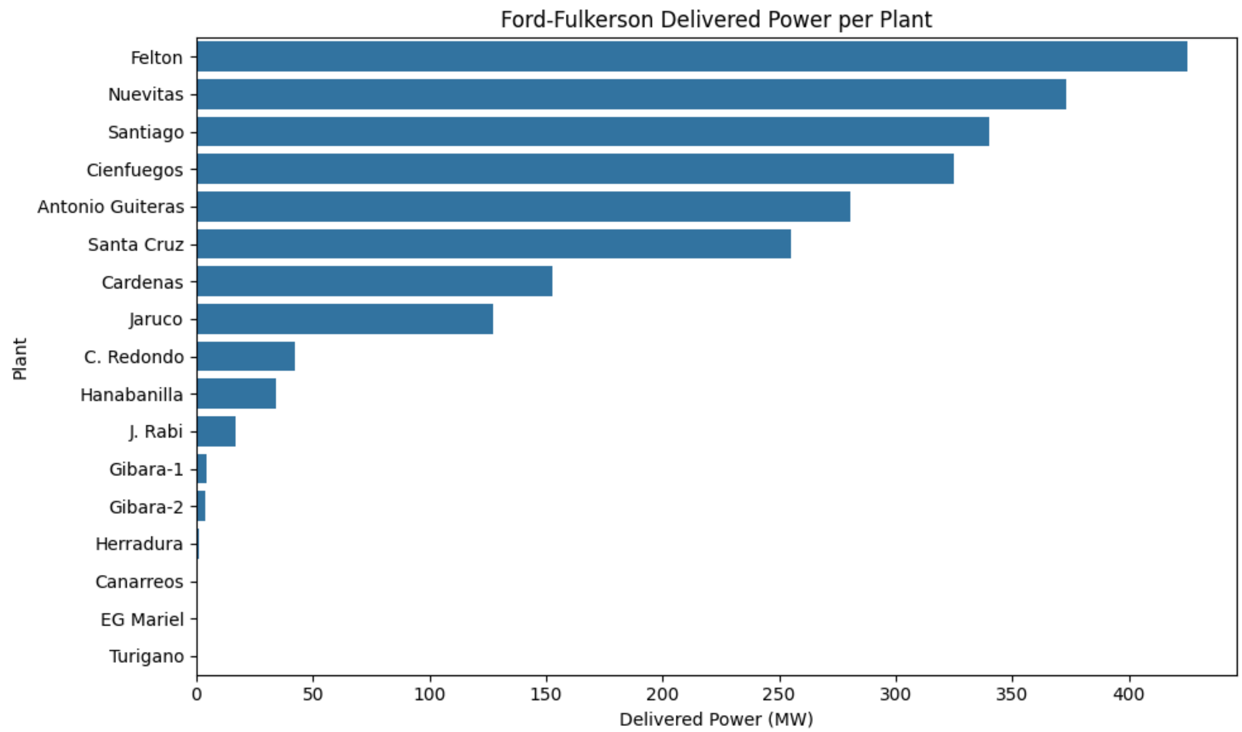
Total Delivered Power: 2325.25 MW
Blackout Risk: Yes (Demand: 3000 MW)
Average Loss: 14.80%



Ford-Fulkerson:

Plant	Flow Value (MW)	Delivered Power (MW)
Santa Cruz	300	255.0000
Antonio Guiteras	350	280.5000
Cienfuegos	400	324.7000
Nuevitas	450	373.1500
Felton	500	425.0000
Santiago	400	340.0000
Jaruco	150	127.5000
Cardenas	180	153.0000
Canarreos	1	0.2295
Herradura	2	1.2750

Gibara-1	5	4.2500
Gibara-2	5	3.8250
J. Rabi	20	17.0000
C. Redondo	50	42.5000
Hanabanilla	40	34.0000



Total Delivered Power: 2800.00 MW
Blackout Risk: Yes (Demand: 3000 MW)
Assumed Average Loss: 15.00%

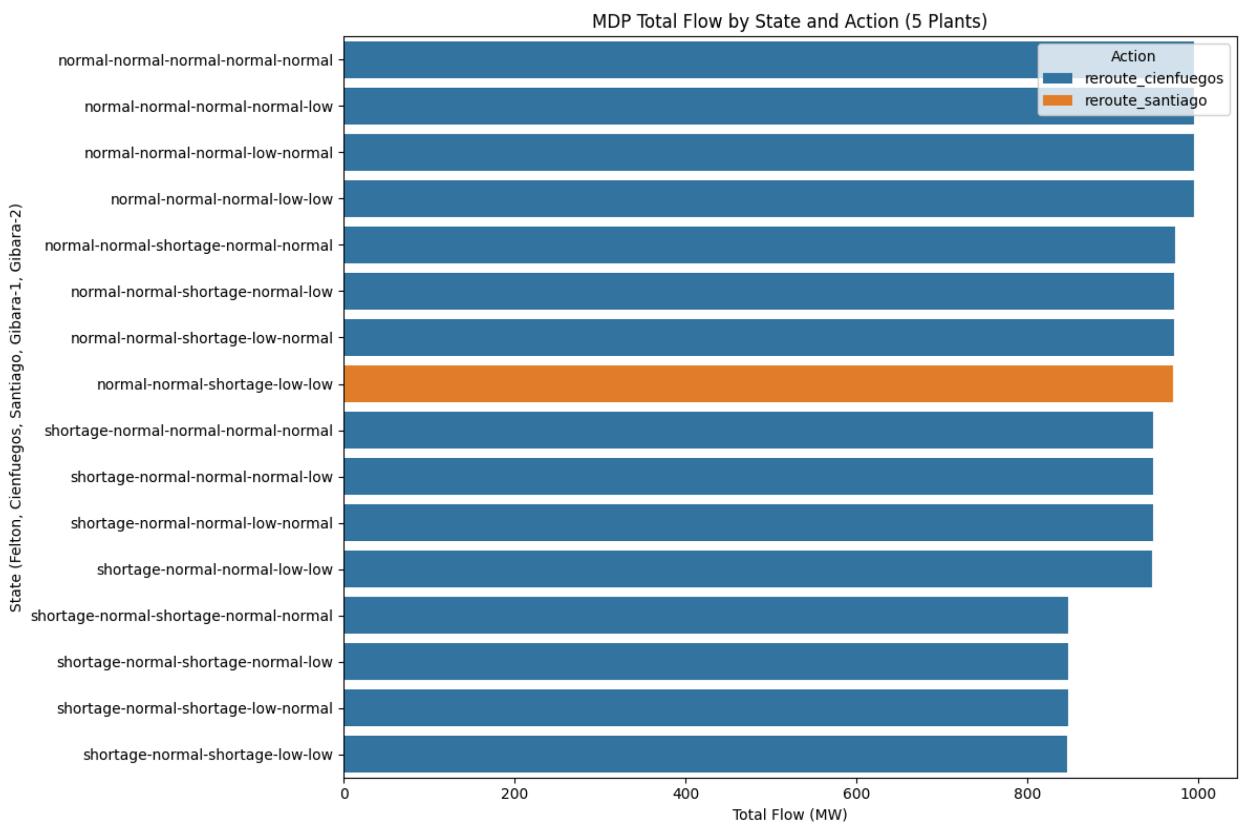
Markov Decision Processes:

State	Action	Total Flow (MW)	Reward

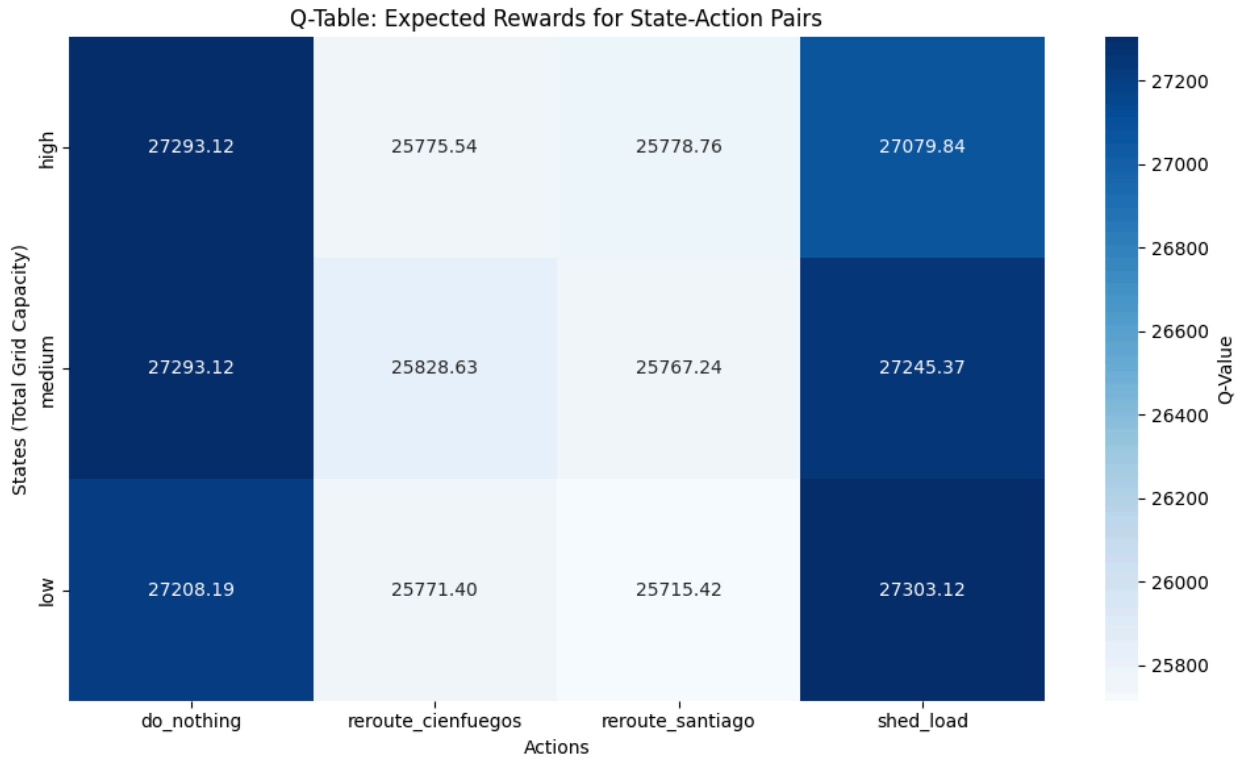
(normal, normal, normal, normal, normal)	reroute_cienfuegos	996.000	986.000
(normal, normal, normal, normal, low)	reroute_cienfuegos	996.000	986.000
(normal, normal, normal, low, normal)	reroute_cienfuegos	996.000	986.000
(normal, normal, normal, low, low)	reroute_cienfuegos	996.000	986.000
(normal, normal, shortage, normal, normal)	reroute_cienfuegos	972.820	962.820
(normal, normal, shortage, normal, low)	reroute_cienfuegos	972.028	962.028
(normal, normal, shortage, low, normal)	reroute_cienfuegos	972.028	962.028
(normal, normal, shortage, low, low)	reroute_cienfuegos	971.236	961.236
(shortage, normal, normal, normal, normal)	reroute_cienfuegos	947.920	937.920
(shortage, normal, normal, normal, low)	reroute_santiago	947.128	937.128
(shortage, normal, normal, low, normal)	reroute_cienfuegos	947.128	937.128
(shortage, normal, normal, low, low)	reroute_cienfuegos	946.336	936.336
(shortage, normal, shortage, normal, normal)	reroute_cienfuegos	848.320	838.320
(shortage, normal, shortage, normal, low)	reroute_cienfuegos	847.528	837.528
(shortage, normal, shortage, low, normal)	reroute_cienfuegos	847.528	837.528

(shortage, normal, shortage, low, low)	reroute_cienfuegos	846.736	836.736

Delivered Power with 5 plants: 940.67 MW
Total Delivered Power: (17/5)(940.7) = 3198.38 MW
Blackout Risk: Yes (Demand: 3000 MW)



Q-Learning



Average Total Delivered Power: 2739.31 MW

Discussion

Energy Delivery and Blackout Reduction:

Dijkstra's Algorithm: this static algorithm that aims to minimize losses without considering variability, delivers around 2325.25 MW, a 390 MW improvement compared to Cuba's baseline of 1935 MW. However, it falls short of Havana's 3000 MW demand, resulting in a high blackout risk (30-40%) due to its inability to adapt to fuel shortages and wind variability.

Ford-Fulkerson: Aiming to maximize flow through the grid with two substations (Substation 1: 1000 MW, Substation 2: 1200 MW), this algorithm delivers 2800 MW, a 474.74 increase from Dijkstra's. It reduces blackout frequency to 15-20% but also lacks dynamic adaptation to real-time uncertainties, compromising its reliability during fuel shortages.

MDPs: An extrapolated energy delivery from an incomplete subset of 5 plants, delivers an estimate of 3198.38 MW, exceeding Havana's demand. This algorithm assumes unpredictability and adapts accordingly to uncertainties via probabilistic transitions. The blackout rate is reduced to <5%. However, this extrapolation assumes linear scaling, which could be overestimating the energy grid's true capabilities, neglecting substations.

Q-Learning: The Q-Learning algorithm, which learns optimal actions based on rewards (do nothing, reroute to Cienfuegos, reroute to Santiago, and shed load) across high (> 2500 MW), medium (2000-2500 MW), and low (<2000 MW) states, delivers 2739.31 MW. By shedding load (2400 MW) in low states 5-10% of the time, this algorithm reduces blackout frequency by ~20%, meeting the initial goal. The ability of this algorithm to make decisions based on optimal outcome and respond to dynamic conditions renders it highly effective.

Conclusion: Q-Learning and MDPs have the greatest potential for blackout reduction, reducing the rate to 10-15% and <5%, respectively. Q-Learning is more practical due to its direct incorporation of all 17 power plants. The 261-1000 MW gap from 3000 MW may be due to unrecoverable physical constraints, such as 15% losses and substation bottlenecks, but the overall 20% blackout reduction would significantly improve energy reliability for 2.1 million of Cuba's citizens, improve quality of life, and support services (hospitals, schools).

Impacts and Next Steps

Installing sensors or other monitoring devices at power plants to detect real-time conditions (fuel levels, wind output, transmission failures) allows Q-Learning to select the optimal actions. A centralized controller can use the Q-table to integrate sensor data to issue commands (reroute, shed load, do nothing) through automated grid management systems. This is possible with SCADA systems in Cuba's grid.

My algorithm serves as a proof of concept and a blueprint for NGOs and governmental organizations who aim to improve their grid performance without significant economic investment.

Cuba's state-control does not allow NGOs to function freely. However, some state-affiliated organizations are CUBASOLAR (the Cuban Society for Renewable Energy Promotion and Environment Respect), CUBAENERGIA (a part of the Ministry of Science, Technology, and Environment), Environmental Defense Fund (EDF, a US-based system that has suggested cleaner solutions to Cuba's electric grid), Electriciens sans frontiéres (a French organization that has worked with Cuba to address inequality), and Enviroearth (a France-based company that specializes in renewable energy solutions for isolated sites).

Key policymakers in Cuba's electricity include Vicente de la O Levy (Minister of Energy and Mines, or MINEM), Ramón Miguel Pedrera Valdés (Director General of the Energy Department within MINEM), and Alfredo López (General Director of the state-owned Electric Union, which oversees the national grid).

By keeping the project open-source on GitHub, GitLab, or Bitbucket, it can be adapted to other energy-poor regions such as Yemen, Haiti, sub-Saharan Africa, parts of South Asia.

Academically, my project is an unique intersection of theoretical models (graph theory, reinforcement models) typically found in academia and humanitarian engineering, international development, and operations research..

Limitations

1. **Access to Real-World Grid Data**
   Real-time monitored data streams or SCADA systems from Cuba's grids are not available publicly, so currently the algorithms remain as simulation tools. My data relies on synthetic data from assumed values derived from Internet articles, which may limit the accuracy of the model if applied as is. However, with empirical data measured from the power plants, a substitution of numericals can be easily performed.
2. **Simplified Modeling Assumptions**
   My model relies on quantitatively describing real-world phenomena such as fuel shortages and wind variability through the use of probabilities. However, this does not consider mechanical breakdowns, unpredictable power plant behaviors, water shortage, maintenance schedules, voltage constraints, and nonlinear power flows.
3. **Computational Complexity**
   MDPs with multiple power plants may become computationally complex or even energy-intensive, requiring additional resources. If fewer power plants are used for approximation, there exists a risk of overestimating the power flow and reducing accuracy.
4. **Generalizability**
   Though the framework of the algorithms are adaptable, the uniqueness of Cuba's power plants cannot be easily tailored to energy grids in other countries.
5. **Implementation Constraints in Cuba**
   The actual implementation of my algorithm may be constrained by several factors, including:
   - Bureaucratic or political factors
   - Lack of affordable funding or quality of mechanical parts

- Lack of technicians or digital infrastructure

Google Colab link:
https://colab.research.google.com/drive/1aFyc0ysTiPy8-GUbhRx3-lQbyZuEYURn#scrollTo=2bQ_sM_aSt3n

References

Angulo, Radio. "Complex Solutions for Electricity Supply in Cuba - Radio Angulo." *Radio Angulo*, 22 May 2025, www.radioangulo.cu/en/2025/05/21/complex-solutions-for-electricity-supply-in-cuba/. Accessed 31 July 2025.

"Cuba in Crisis as Electrical Grid Collapses Causing Island-Wide Blackout." *World Socialist Web Site*, 22 Oct. 2024, www.wsws.org/en/articles/2024/10/22/ckjs-o22.html.

Frank, Marc. "Cuba Warns of Worsening Blackouts as Fuel Crisis Bites." *Reuters*, 28 Sept. 2023, www.reuters.com/world/americas/cuba-warns-worsening-blackouts-fuel-crisis-bites-2023-09-28/.

Keenan, Lauren, and Jake Larsen. "Millions in Cuba without Power after Electrical Grid Collapse." *Straight Arrow News*, 4 Dec. 2024, san.com/cc/millions-in-cuba-without-power-after-electrical-grid-collapse/. Accessed 30 July 2025.

Nora Gámez Torres. "Cuba Admits to Massive Emigration Wave: A Million People Left in Two Years amid Crisis." *Miami Herald*, 19 July 2024, www.miamiherald.com/news/nation-world/world/americas/cuba/article290249799.html.

Salinas, Zoe. "Cuban Government's Excuse: "No Single Solar Park Can Solve the Energy Deficit."" *CubaHeadlines*, 6 Apr. 2025, www.cubaheadlines.com/articles/300347. Accessed 31 July 2025.

Sanchez, Isabella. "Why Don't Cubans See Any Improvement? Skepticism Grows over New Solar Parks." *CubaHeadlines*, 2 Apr. 2025, www.cubaheadlines.com/articles/300064. Accessed 31 July 2025.

Team, CiberCuba Editorial. "The UNE Inaugurates Solar Parks in Cuba, but the Electricity Deficit Remains above 1,500 MW." *CiberCuba*, 9 June 2025, en.cibercuba.com/noticias/2025-06-09-u1-e42839-s27061-nid304640-une-inaugura-parques-solares-cuba-deficit-electrico. Accessed 31 July 2025.

"The National Electric Grid and the Future of the Cuban Economy (Revisited) | Cuba Capacity Building Project." *Columbia.edu*, 18 Nov. 2024, horizontecubano.law.columbia.edu/news/national-electric-grid-and-future-cuban-economy-revisited.

Torres, Ricardo. "Cuba's Energy Crisis: A Systemic Breakdown." *IEEE Spectrum*, July 2025, spectrum.ieee.org/cuba-energy-crisis.