A Conceptual Model for Analyzing the Impact of Natural Gas on Electricity Generation Failure during the 2021 Texas Power Outage

Andrew Schaper
Department of Multidisciplinary Engineering
Texas A&M Energy Institute
Texas A&M University
Email: drewjames39@tamu.edu

Le Xie
Department of Computer & Electrical Engineering, and
Texas A&M Energy Institute
Texas A&M University
Email: le.xie@tamu.edu

***Abstract*—The inter-dependence between electrical grid operations and natural gas infrastructure in Texas has been steadily increasing in recent years. The trend has been driven, in part, by the persistent decommissioning of coal-fired power plants and the increasing penetration of renewable generation. Moreover, changes to the type and deployment of natural gas generation facilities over the previous decade have increased the reliance on "just-in-time" natural gas delivery which places the system at increased risk of failure. The purpose of this paper is to delineate previously under-explored drivers of natural gas system operation, present a novel conceptual framework characterizing the integrated system inter-dependencies and outline possible policy measures which would promote enhanced system reliability.**

I. INTRODUCTION

The electric grid in Texas has become increasingly reliant on natural gas as a fuel for electricity generation. Availability of the fuel has been bolstered by horizontal development of shale formations across the United States, unlocking trillions of cubic feet of resource [1]. Lower capital and operating costs, shorter depreciation periods and more modest environmental impact have accelerated wide adoption of new combined-cycle plants for power production [2] [3]. Generation attributed to natural gas within the ERCOT system rose from 38% in 2010 up to 46% in 2020. Meanwhile, generation from coal-fired plants fell from 40% to 18% and generation originating from renewable sources rose from 8% to 25% during the same time frame [4] [5]. Taken together, these three fuel types have comprised a steady and consistently large share of the fuel used to generate electricity in Texas (Fig. 1). The changing generation mix in Texas is consistent with changes occurring across the United States, as coal is phased out in favor of natural gas and renewable energy. This transition presents a number of challenges stemming from increased grid interdependence with the natural gas system. The extreme cold weather combined with a "just-in-time" operating philosophy led to fuel shortages which were exacerbated by generating plants operating without backup fuel and privately-owned gas storage facilities which had sold working gas reserves in advance of the storm. Prior work has shown that interruptions within the natural gas transmission system can have significant impacts on system-wide reliability [6] [7]. These unique system interrelationships will continue to impact the Texas grid system, especially as reliance on both natural gas and renewable generation grow into the future [8].

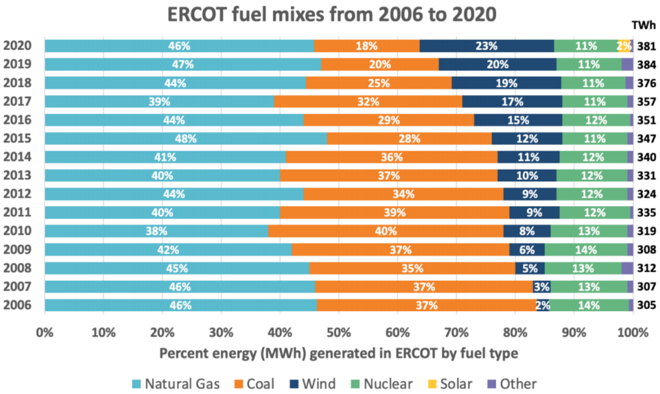

Fig. 1: ERCOT fuel mix from 2006 through 2020, Percent energy (MWh) generated in ERCOT by fuel type [5]

The purpose of this paper is to demonstrate the impact of natural gas midstream infrastructure on grid resilience, to outline a conceptual framework for consideration in future system modeling and to propose policy actions which may mitigate the impact of system inter-dependencies as reliance on natural gas generation.

II. SYSTEM INTER-DEPENDENCIES

A. *Natural Gas Processing & Compression Infrastructure*

During Winter Storm Uri, natural gas processing and compression systems were disrupted because of weather-related and operational issues stemming from the storm [5]. These disruptions compounded an already dire production shortfall in the upstream sector which is beyond the scope of this work. We demonstrate the potential for significant gas generation impact based simulated outages at natural gas processing sites.

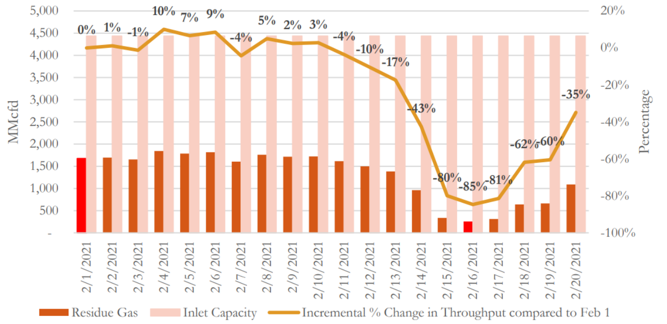

Fig. 2: Throughput Gas for Permian Basin Processing Plants during Winter Storm Uri, Sample of 27 Facilities [5]

Certain transmission and distribution service providers (TDSPs) serving extensive areas of west Texas noted that as many as 133 pieces of critical natural gas infrastructure had to be added to a "do not turn off" list during the storm, with many of these facilities located in the Permian Basin [5]. Upstream operators in the region produce a significant amount of crude oil and natural gas that contribute meaningfully to the Texas exploration and production industry. The inability of TDSPs to identify critical natural gas processing and compression facilities was related to voluntary forms not completed by facility operators in advance of the event [5].

In terms of the network topology, each producing basin is represented as a single upstream "node" with outflow of natural gas served by dozens of processing and compression facilities. We demonstrate that improvement in critical load designations could have dramatically improved natural gas flows from the region and prevented adverse physical and economic constraints that negatively impacted generation.

B. Natural Gas Storage

Texas is home to 40 natural gas storage sites with a total maximum withdrawal rate of 17.5 Bcf/d [5] [9]. These facilities often make use of underground depleted salt caverns to serve as a "reservoir" for natural gas volumes which can be either injected or produced from one or more wells in the complex. Natural gas is sourced from and delivered to large pipelines that carry the fuel throughout the Texas market, serving residential, industrial, and commercial demand [10]. The facilities are typically owned and operated by interstate pipeline companies, intrastate pipeline companies, local distribution companies (LDCs) and independent storage service providers; however, natural gas within the underground storage complex is not necessarily owned by the operator of the facility [10]. Interstate pipeline companies, which control certain sites, can use them for load balancing and system supply management [10]. More recently, a trend toward deregulation and so-called "open access" provisions promulgated by FERC Order 636 have encouraged entrepreneurial ownership in these facilities [10].

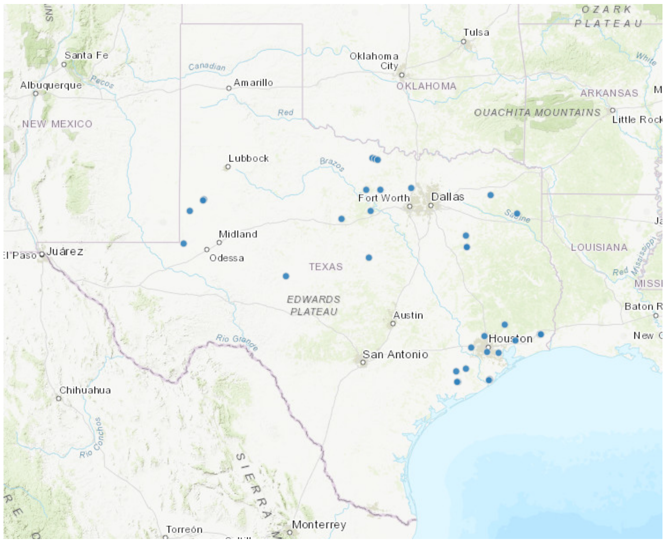

Fig. 3: Texas Natural Gas Storage Sites, Energy Information Administration, U.S. Energy Atlas, [9]

Natural gas prices have been shown to impact economic dispatch by Ordoudis et al and others [11]. A retrospective sampling of withdrawal rates from natural gas storage facilities during the storm revealed that many sites began rapidly evacuating their reserves to serve demand on February 9th, days in advance of the major blackouts [5]. Elevated commodity prices prior to the storm provided an economic incentive for operators to withdraw gas from storage. By way of example, natural gas prices during the week of February 1st averaged \$3.12/mmbtu, while natural gas prices averaged \$4.63/mmbtu the week of February 8th (an increase of 48.3%) [13]. A price increase of this magnitude provides a market signal for participants to sell available working gas reserves [10]. Unfortunately, the rapid withdrawal left many Texas storage sites without spare natural gas as Texas entered a period of record-setting electricity demand [5].

The conceptual model proposed in this paper provides a framework to anticipate the availability of natural gas from storage sites based on the prevailing commodity price environment. The profit expectation for a given volume of natural gas held in storage can be expressed through the following equation:

$$P = v * e * (p2 - p1)$$

where P = absolute economic profit in dollars, v = natural gas volume in thousand cubic feet, e = energy content in million British thermal units per thousand cubic feet, p2 is final price in dollars per million British thermal units and p1 is final price in dollars per million British thermal units.

We posit that examining the absolute economic profit potential expressed above allows conclusions to be drawn about the probability of inflow or outflow at a given facility. The impact of commodity pricing on the physical gas supply chain and the resulting impact to fuel availability for generation are critical considerations explored in this work.

III. Conceptual Model of Gas-Electric System

A novel conceptual model can be derived by segmenting natural gas infrastructure and the electric grid into their constituent components, identifying key links between the systems and associating the availability of these links with probability distribution functions. The segmentation highlights key interdependencies and allows for a probabilistic assessment of natural gas volumes available for generation (Fig. 4).

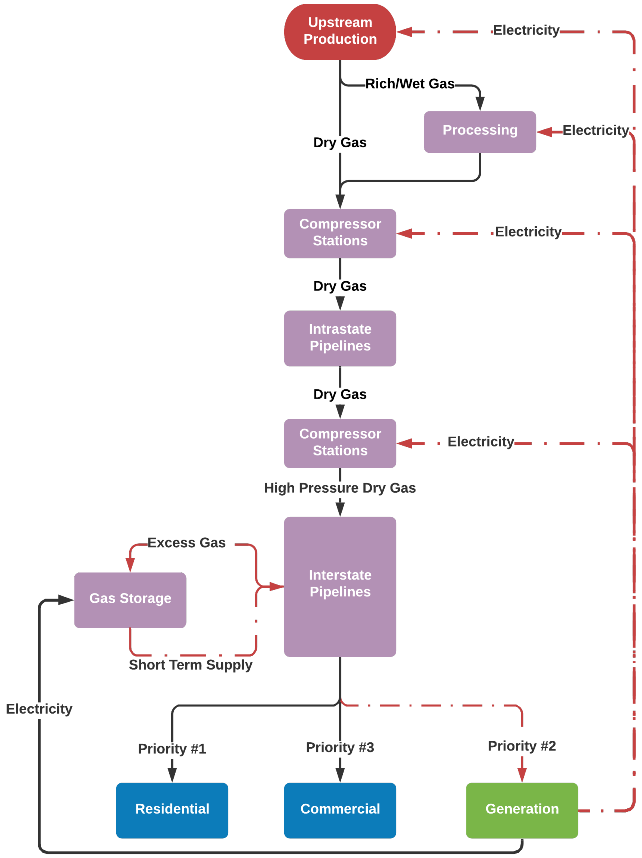

Fig. 4: Conceptual Model of Natural Gas System & Electric Generation Infrastructure Coupling. Red dashed lines represent key feedback loops modeled as part of this analysis.

Failures occurring in the standalone “Gas Storage” node are simulated by applying custom discrete random variables intended to capture the inflow or outflow state of the sites. The probability of each state is determined through a matrix of anticipated operator behavior under different natural gas pricing conditions (Fig. 5). For “Processing” and “Compressor” nodes, production is aggregated according to basin (“Permian Basin” or “Other Basin”). Because the operation of this equipment is discrete insofar as it is either operating (with electrical service) or deemed unavailable, a Bernoulli Distribution function is utilized to represent critical infrastructure used to process and transmit natural gas.

Input variables to the aforementioned functions included both the likelihood of incorrect resource designation for gas processing and compressor facilities which is conveyed in Figure 5 as well as the commodity price for Henry Hub natural gas following a distribution as described below in Figure 6. In the instance of the latter input, historical natural gas prices dating back to 1997 were sampled from the EIA. The ”NG Price Delta” value presented in Figure 6 is calculated by using p2 and p1 values one week apart time series is utilized to form the basis of the standard deviation measure evident in the histogram. [13].

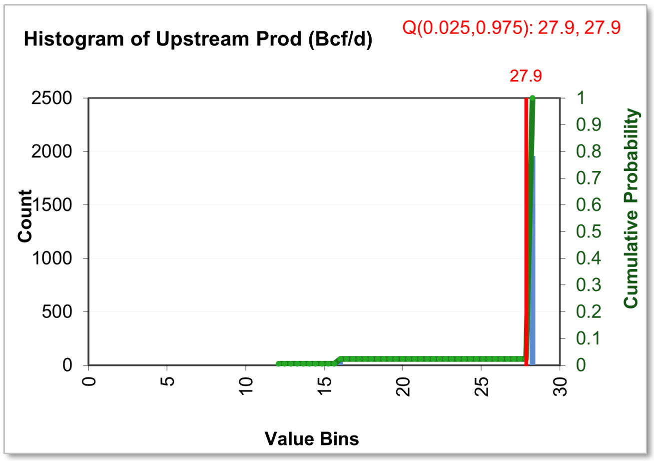

Fig. 5: Theoretical upstream production with access to the interstate gas market based on constituent probability functions for midstream infrastructure availability, n = 2000 observations

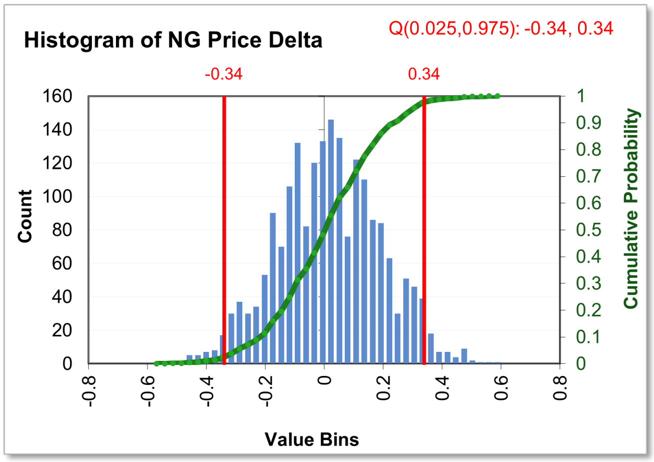

Fig. 6: Monte Carlo approximation of natural gas spot price relative to week-prior average price, distribution based on EIA Henry Hub Pricing data from 1997 to current, SD = \$0.175/mmbtu, n = 2000 observations

By utilizing probability functions to describe these input variables and allowing for approximation of the system as a simplified network, this conceptual approach reveals the critical importance of midstream system elements. Natural gas production out of storage facilities can be estimated using the

	Price Variance Relative to Prior Week ($/mmbtu)				
	($0.350)	($0.175)	$0.000	$0.175	$0.350
Flow State	**(-2xSD)**	**(-1xSD)**	**(0xSD)**	**(1xSD)**	**(2xSD)**
-100%	85%	20%	5%	0%	0%
-25%	10%	50%	20%	5%	0%
0%	5%	25%	50%	25%	5%
25%	0%	5%	20%	50%	10%
100%	0%	0%	5%	20%	85%
	100%	100%	100%	100%	100%

Fig. 7: Natural gas storage facility operator behavior as a function of historical commodity price behavior

“Flow State” matrix provided in Figure 7. Resultant natural gas production from storage facilities is found in Figure 8.

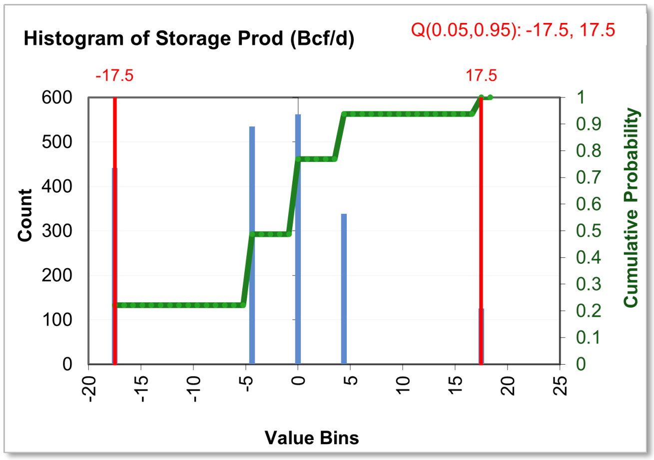

Fig. 8: Estimated production from Midstream Natural Gas Storage Facilities, projected as a function of both the theoretical maximum outflow capacity (17.5 Bcf/d) as well as the anticipated operator behavior in relation to profit potential, as judged by spot prices relative to historical averages, n = 2000 observations

The resulting delivery of natural gas for electricity generation is considered in the context of both processing & compression downtime and natural gas storage facility operating status.

The simulation using this model framework reveals that there is less than a 0.35% chance that the theoretical natural gas-fired generation falls below 10,000 MW at any given point in time, (excluding the influence of other system factors such as maintenance or de-rating). For comparison, the April 2021 net generation from natural gas in Texas equaled 22,013 MW. To accommodate this computation, a natural gas flow rate-to-power ratio of 1 Bcf per day per 2,706 MW of generation was implemented to reflect current generation combined cycle gas turbines. Supply was segmented according to a historically consistent percentage allocation of natural gas to the needs of electricity generation. This simplified approach is intended to reflect an idealized system; however, the use of higher heat rates (less efficient generation as is the case in the Texas grid today) would raise the probability of a shortfall relative to the value stated above.

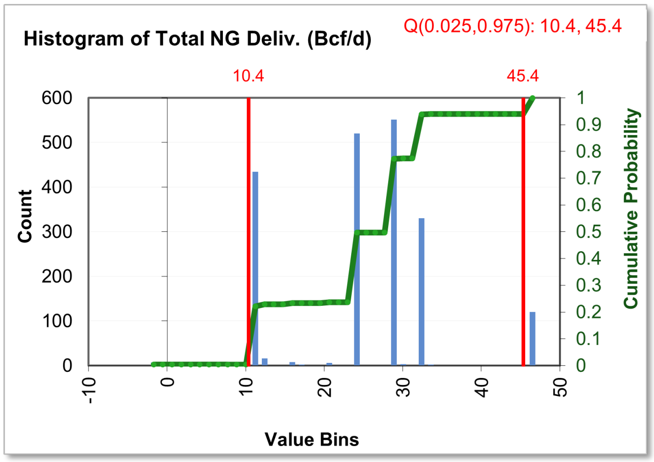

Fig. 9: Total Available Natural Gas for Delivery to Electrical Generation as a function of both the sum of upstream capacity by basin and inflow or outflow from storage, n = 2000 observations

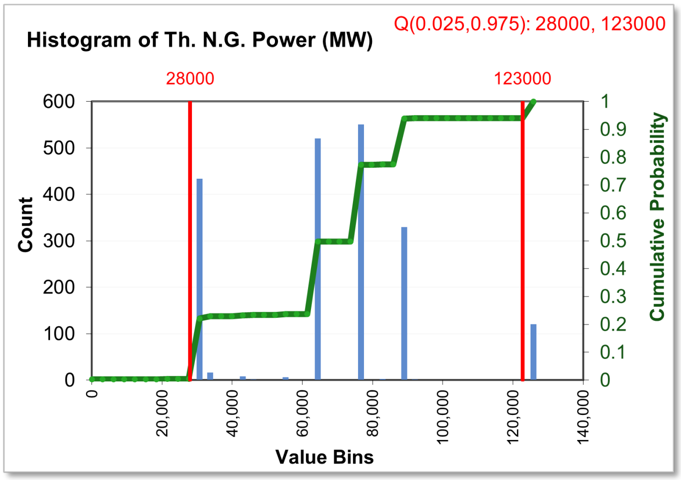

Fig. 10: Theoretical power available from natural gas assuming January 2021 allocation to end users remains constant, n=2000

IV. POSSIBLE POLICY MEASURES FOR MITIGATING FUTURE OUTAGE RISKS

There are a number of policy topics at the nexus of natural gas and electricity systems which deserve further investigation. In particular, there are two key elements which, if addressed, could substantially alleviate problems arising from natural gas-electricity coupling. First, regulatory changes which acknowledge the important role of the natural gas system in electrical generation are needed. Separated regulatory oversight runs counter to promoting operational stability (e.g. dynamic gas delivery, compression requirements), necessitating coordination [14]. This issue was identified and assessed by Zlotnik et al. as part of a hypothetical fully integrated gas-electric approach [1]. There are examples of both physical (load shed) and economic (pricing) disruptions which occurred during Winter Storm Uri that may have been avoided through joint coordination. Second, natural gas fuel shortages were exacerbated by an apparent lack of gas in storage during the week of February 15 [5]. The absence of physical reserves left no room for error in the supply chain.

A. *Regulatory Cohesion*

Policy makers should consider establishing new regulatory standards for critical natural gas installations that are consistent with the objectives of grid reliability. Natural gas processing and compressor stations should no longer be eligible for ERCOT's Emergency Response Service (ERS) program, which encourages voluntarily shut down of facilities to serve load [15]. TDSPs should ensure entities serving as ERS resources are designated to avoid load shed of response infrastructure (emergency power providers). This action prevents isolation of key downstream natural gas generating resources during rolling blackout condition.

Texas authorities must coordinate the activities of the Texas Railroad Commission (TRRC) and ERCOT to ensure critical flow paths remain intact [16]. TRRC should consider re-prioritizing natural gas delivery to power plants during ERCOT emergency conditions; universal first priority for residential natural gas delivery must be re-evaluated.

B. *Infrastructure & Strategic Reserves*

Many natural gas storage sites in Texas have reserves which are controlled by profit-seeking private enterprises [9] [10]. The companies inject and withdraw natural gas to meet their own financial objectives with little regard to supply requirements in the generation sector. The gas being stored at these sites cannot be considered to serve a role as a strategic resource unless it is managed under a common administrative system with the electrical grid. This is not the case today.

This problem could be remedied by development of strategic natural gas reserves in areas which are co-located with generation or otherwise vulnerable to upstream shortages (such as those which occurred in the Permian Basin). Such an idea has been previously explored By Diagoupis et al. in Greece, where interdependence of natural gas and electrical grid have proven to be a challenging problem [6] [2]. The development of new strategic natural gas storage could include partial or complete economic ownership of existing facilities by the State or, alternatively, the construction and operation of new storage sites. The fundamental economic factors driving private companies to produce natural gas during time of price volatility may prevent the use of existing facilities as a buffer when volumes become unavailable.

V. CONCLUSION

We propose a conceptual model to identify key interdependencies of regional natural gas and electric generation infrastructure during the 2021 Texas power outage. Based on this conceptual model, improvements to regulatory and infrastructure policies are proposed as a means to mitigate the potential impact of power outages arising from foreseeable failure conditions. Future expansion of this work would investigate the application of statistical distributions to more nodes within the conceptual model, explore temporal dependencies in available reserves at natural gas storage sites, expand the volumetric flow rate-to-power input variable assignment to reflect current and projected installed capacity and investigate the application of this analysis to other extreme weather-induced events.

ACKNOWLEDGEMENT

This work is supported in part by Texas A&M Energy Institute, and in part by the National Science Foundation under Grant CMMI-2130945. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] Zlotnik, L. Roald, S. Backhaus, M. Chertkov and G. Andersson, "Coordinated Scheduling for Interdependent Electric Power and Natural Gas Infrastructures," in IEEE Transactions on Power Systems, vol. 32, no. 1, pp. 600-610, Jan. 2017, doi: 10.1109/TPWRS.2016.2545522.

[2] Theodoros D. Diagoupis, Panagiotis E. Andrianesis, Evangelos N. Dialynas, "A planning approach for reducing the impact of natural gas network on electricity markets," in Applied Energy, Volume 175, 2016, Pages 189-198, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2016.05.006.

[3] M. Shahidehpour, Yong Fu and T. Wiedman, "Impact of Natural Gas Infrastructure on Electric Power Systems," in Proceedings of the IEEE, vol. 93, no. 5, pp. 1042-1056, May 2005, doi: 10.1109/JPROC.2005.847253.

[4] U.S. Department of Energy, Energy Information Administration, Independent Statistics & Analysis. Electricity Data Browser. (2021, May). Retrieved from https://www.eia.gov/electricity/data/browser.

[5] C. W. King, J.D. Rhodes, J. Zarnikau, N. Lin et al., "The Timeline and Events of the February 2021 Texas Electric Grid Blackouts", The University of Texas Energy Institute, July 2021.

[6] T. D. Diagoupis, E. N. Dialynas and L. G. Daoutis, "Reliability Assessment of Natural Gas Transmission Systems and their Impact on the Operational Performance of Electric Power Systems," 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2012), 2012, pp. 1-7, doi: 10.1049/cp.2012.2029.

[7] Dongqi Wu, Xiangtian Zheng, Yixing Xu, Daniel Olsen, Bainan Xia, Chanan Singh, Le Xie, "An open-source extendable model and corrective measure assessment of the 2021 texas power outage," in Advances in Applied Energy, Volume 4, 2021, 100056, ISSN 2666-7924,https://doi.org/10.1016/j.adapen.2021.100056.

[8] Enrica Raheli, Qiuwei Wu, Menglin Zhang, Changyun Wen, "Optimal coordinated operation of integrated natural gas and electric power systems: A review of modeling and solution methods," in Renewable and Sustainable Energy Reviews, Volume 145, 2021, 111134, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.111134.

[9] U.S. Department of Energy, Energy Information Administration, Independent Statistics & Analysis. Energy Atlas: "Underground Natural Gas Storage". (2021, August 15). Retrieved from https://atlas.eia.gov/datasets/natural-gas-underground-storage/

[10] U.S. Department of Energy, Energy Information Administration, Independent Statistics & Analysis. "Basics of Underground Natural Gas Storage". (2015, November 16). Retrieved from https://www.eia.gov/naturalgas/storage/basics/

[11] Christos Ordoudis, Stefanos Delikaraoglou, Jalal Kazempour, Pierre Pinson, "Market-based coordination of integrated electricity and natural gas systems under uncertain supply," in European Journal of Operational Research, Volume 287, Issue 3, 2020, Pages 1105-1119, ISSN 0377-2217, https://doi.org/10.1016/j.ejor.2020.05.007.

[12] U.S. Department of Energy, Energy Information Administration, Independent Statistics & Analysis. “Dry Shale Gas Production Estimates by Play”. (2021, July 15). Retrieved from https://www.eia.gov/naturalgas/data.php

[13] U.S. Department of Energy, Energy Information Administration, Independent Statistics & Analysis. “Henry Hub Natural Gas Spot Prices”. (2021, August 15). Retrieved from https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm

[14] Talebi, A. Sadeghi-Yazdankhah, M. A. Mirzaei and B. Mohammadi-Ivatloo, “Co-optimization of Electricity and Natural Gas Networks Considering AC Constraints and Natural Gas Storage,” 2018 Smart Grid Conference (SGC), 2018, pp. 1-6, doi: 10.1109/SGC.2018.8777813.

[15] Electric Reliability Council of Texas (ERCOT). “Emergency Response Service. (2021, April 2). Retrieved from http://www.ercot.com/services/programs/load/eils

[16] Texas Railroad Commission, “About Us”. (2021). Retrieved from https://www.rrc.texas.gov/about-us/