Decarbonize ERCOT with Large Thermal Energy Storage

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Abstract—The purposes of this paper are to show (1) the benefits of Charles Forsberg's large low-cost thermal Crushed Rock Ultra-large Stored Heat (CRUSH) in ERCOT and (2) an hourly dispatch electrical simulation model that has been written in Microsoft Excel for transparency and widespread use. The model has a sophisticated storage algorithm and captures how effectively all the resources are being utilized concerning energy used and not used by each resource. This allows maximum wind and solar penetration without over-investments. The dispatch is done in a logical sequence from base loaded generation to peaking. 100% fossil fuel free generation is achieved when no gas peaking capacity or energy is needed or used.

Index Terms— Nuclear Thermal Storage, Storage Algorithms, Winter Storm Electric Reliability, Grid Decarbonization, Gas Peaking Generation

Introduction

The benefits of large low-cost thermal Crushed Rock Ultra-large Stored Heat (CRUSH) [1-4] has been given a NASA Technical Readiness Level 4+ status [5]. CRUSH storage is charged with nuclear thermal energy and discharged supplying energy and power to ERCOT. The CRUSH generators are sized to harmonize wind, solar, and demand and also lessen or remove the need for gas backup generation during a severe winter storm such as Uri.

Storm Uri in February 2021 was an especially difficult time for ERCOT, having narrowly missed a complete blackout of the region as the below freezing weather ran for 100 hours longer than ERCOT expected. Normally a freezing winter weather period is brief. The extended cold weather with multiple fronts during the Uri event exhausted gas supplies for generation plants which had not been designed with oil backups. When gas generation that powered the electric pumps of the gas supply system was curtailed, the loss of generation compounded, and a near blackout was averted by an extreme load shedding exercise that left much of the grid without power for days. Hundreds of people died in the cold.

In order to make the grid reliable in extremely cold and hot weather, sufficient capacity and energy must be available. In the winter, solar energy production is lower, and wind will have periods of intermittency. Although the cold fronts produced wind power at the start of Uri, in the closing days of Uri the fronts passed, but the cold continued. Wind and solar advocates believe adding more wind and solar is the solution; however, the Excel program in this paper shows too much energy is thrown away by over-investing in renewables.

Nuclear also has an over-investing MW capacity problem. If nuclear capacity is added to meet peak load demands, then nuclear capacity may be underutilized during most of the year. The proper amount of nuclear and storage can be found using this spreadsheet.

I. Hourly Dispatching Logic

The calculations are from left to right on each line of the Excel spreadsheet and then advance to the next line for each hour of a test year. The last calculation on a line is the amount of fossil fuel MWs needed that hour to serve the load. All fossil fuels are treated as a single generation resource called gas peaking. The program calculates gas peaking capacity and energy as needed. The decarbonization objective is to minimize the gas peaking capacity and energy.

ERCOT's historical 2022 dispatch is modeled in file ERCOT22A [6] to verify the dispatch spreadsheet matches what actually happened. Generation serving load is calculated from left to right for the non-fossil fuel resources tied directly to the grid. They are dispatched in the order of nuclear, wind, and solar. Excess generation MWs not used are available for charging the battery. Since 2022 had no excess non-fossil capacity, the battery energy storage is zero. The ERCOT22A plot of fossil fuel energy each hour is shown in Figure 1. The calculated 59% fossil energy is close to the actual ERCOT 60%.

There are three study cases. ERCOT22A recreates the actual 2022 system dispatch. ERCOT22C [7] is a 2021 simulation of storm Uri with thermal storage and new nuclear added for the purpose of minimizing or eliminating fossil fuels. ERCOT22C1 [8] is the ERCOT22C case with 2022 historical profiles of demand, wind, and solar [9]. ERCOT 2022 historical data captures winter storm Elliott.

II. Spreadsheet Initial data Setup

The first column of the spreadsheet is the historical year, month, day, and hour entered as a single integer header yyyymmddhh highlighted in yellow. The header in yellow means the entire column of numbers is entered manually as a paste operation. The date and time as integers were created externally with a computer program.

Having the date and time as a single integer simplifies editing and sorting the data with a text editor before it is copied into the spreadsheet. Since the date integer is not used in any calculations or tests, any format of the time stamp in the spreadsheet is acceptable. Also acceptable is the use of daylight savings time and leap years. The spreadsheet performs average energy cost calculations for a year, so it is designed to model just one year at a time. Modeling one year means testing and designing the power supply for a historical year's weather and demand with the profile scaled to represent a future year. Use of a 32 bit integer time stamp has a future date limitation. The year 2148010101 is a larger integer than can be contained in 32 bits. Therefore the calendar year 2147 is the last year this format can be used for the entire year time stamp.

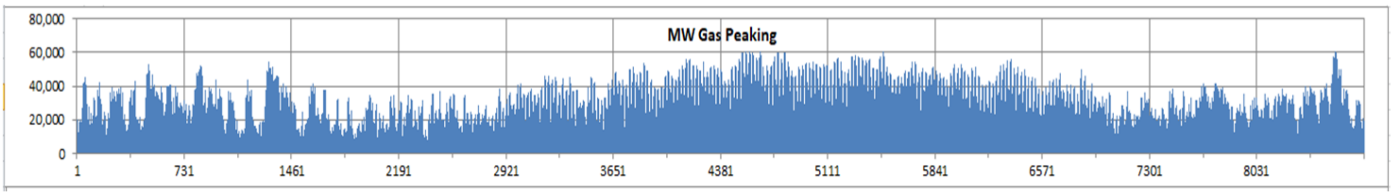

Figure 1. ERCOT22A Hourly Fossil Fuel MWs Dispatched Versus Hour of the Year

ERCOT's demand, wind, and solar hourly MWh/h for 2021 and 2022 are externally converted into per unit profiles [9]. The peak demand hour each year will have a per unit value of 1. Wind and solar profiles are normalized each hour to the ERCOT installed nameplate capacities. The per-unit demand, wind, and solar data under the yellow headers are manually copied into the spreadsheet. When new studies are run, each profile is converted into hourly MWs from a single number in yellow over the MW columns. These MWs are maximum values specific to each study.

III. Energy Storage

The electrical battery storage in 22A or the thermal energy storage coupled to nuclear reactors in 22C and 22C1 is placed in the dispatch sequence after the grid connected resources serve load directly. The S_{max} storage capacity in MWh electrical is entered in the yellow cell above the hourly storage column. Non-fossil excess energy charges the storage in 22A, and all thermal energy charges the storage in 22C and 22C1. Storage serves the load preceding the gas peaking dispatch.

The storage algorithm is contained within a single Excel cell as a set of conditional tests for storage capacity as energy is moving in and out of the storage. To better understand the storage logic, the following labels are used instead of the spreadsheet cell labels.

S is the total storage MWh at the end of the previous hour

S^+ is the total storage MWh at the end of the current hour

S_{max} is the total MWh storage maximum capacity

S_{min} is the storage minimum capacity = 0 MWh

G is the sum of excess nuclear, wind, and solar in 22A or

G is the nuclear reactor MWe thermal in 22C and 22C1

D is the MWh/h demand (load) remaining to be served

E is the per unit of G efficiency in charging, i.e. 0.9 = 90%

R is the shunt leakage MWh/h loss of energy each hour

The Excel formula in the spreadsheet for calculating the amount of energy storage each hour is:

IF(S+G*E-D-R>S_{max},S_{max},IF(S+G*E-D-R)<0,0,S+G*E-D-R))

The above formula states that if the energy sent to storage causes the storage to be over-charged, then the storage level is set to its maximum level (fully charged). If the amount of energy taken out of storage causes the storage to be less than zero, then the amount of energy in the storage is set to zero (fully discharged). If the storage falls between 0 and S_{max}, then the amount of storage MWh for this hour is set to the value of S+G*E-D-R.

The energy $S–S^+–R < 0$ is charging the storage. The energy $S–S^+–R > 0$ is serving the remaining load. If the remaining load is completely served, then there will be no gas peaking MWs this hour.

Thermal storage MWe are expressed in terms of the electrical energy produced from storage. The conversion of heat to electricity efficiency may be approximately 33%. The heat energy stored is about three times the electrical energy produced. This paper treats the stored heat energy in terms of the electrical kWh produced.

The storage is assumed to be fully charged at the beginning of the study period. It should also be fully charged at the end of the study period in type 22A cases using electrical storage. If battery storage is not fully charged at year's end, there is an imbalance between the start and end of the year storage. This creates a phantom energy source which is an imbalance in the total production and consumption of energy during the year. Adding battery storage to 22A will demonstrate the battery is quickly discharged. In the thermal storage cases 22C and 22C1 the thermal battery is not fully charged at the end of the period; however, the electrical annual energy is balanced. Charging fully at the end of the period is only required when battery storage is modeled.

IV. ERCOT Case Descriptions

All the cases model a 2022 summer peak demand of 80 GW, although the actual was 79.83 GW with 62% load factor. The 2021 summer peak demand was 73.6 GW. The 2023 and 2024 peak demands were close to 85.5 GW. ERCOT's load is growing.

ERCOT22A has 5 GW nuclear that is currently in operation. The wind and solar historical MWs are per unitized to their nameplate capacities each hour. Although there was continuous wind and solar growth historically, 36 GW wind and 12 GW solar in case 22A are the approximate nameplate values at the end of the 2022 summer. Case 22A assigns 60.8 GW of gas peaking and dispatches it at 48% capacity factor consistent with Figure 1. The 2022 winter storm Elliott occurs in December with a peak demand of 92% of the 2022 summer peak demand.

ERCOT22C models the 2021 demand, wind, and solar hourly profiles with a 2022 peak demand of 80 GW. A completely new generation lineup is used. Winter storm Uri in February occurs before the summer peak of 2021 at 86% of the summer peak. The thermal storage of 30 MWe at 200 hours (6000 GWh) allows ERCOT to meet demand through winter storm Uri without dispatching fossil fuels.

Case 22C has 5 GW existing base loaded nuclear, 38 GW wind, 58 GW solar, 30 GWe thermal nuclear with seasonal outages scheduled, and 63 GWe generators taking their energy from storage. The wind is increased only a small amount over 36 GW in 2022 due to ERCOT's transmission limitations. The 58 GW solar is economically useful for summer peaking providing both capacity and energy. Solar is located geographically throughout ERCOT as close to load as possible, so it needs less transmission than wind. Thermal storage, rather than batteries, serves the role of supplying solar energy after sundown. The thermal nuclear and its electric generators are sized optimally to best serve the entire 2022 year with 2021 profiles. The MW capacity amounts of 38 GW wind and 58 GW solar are nearly fully utilized in 22C and 22C1 because of the very large amount of storage available. Without it excess energy is lost.

ERCOT22C1 is the same generation mix as ERCOT22C except the 2022 hourly profiles are used instead of 2021 profiles. In order to not need fossil fuels, the thermal nuclear had to be increased to 30.5 GWe for 200 hours (6100 GWh) storage. The storage electric generators dropped to 61 GW, which is automatically calculated by the program in the same manner as the amount of gas peaking.

Figure 2 shows the ERCOT22C thermal maintenance schedules for spring and fall. The amount of energy stored in the thermal storage is plotted for each hour of the year, which uses 2021 profiles and 2022 hourly peak demand of 80 GW. The storm Uri 2021 profile in February nearly completely discharges the thermal storage but leaves some summer 2021 profile energy in reserve.

Figure 3 shows the ERCOT22C1 thermal maintenance schedule which differs slightly from 22C. The thermal energy stored throughout the year is also different because the weather is different. Storm Elliott is in December on the right end of the graph.

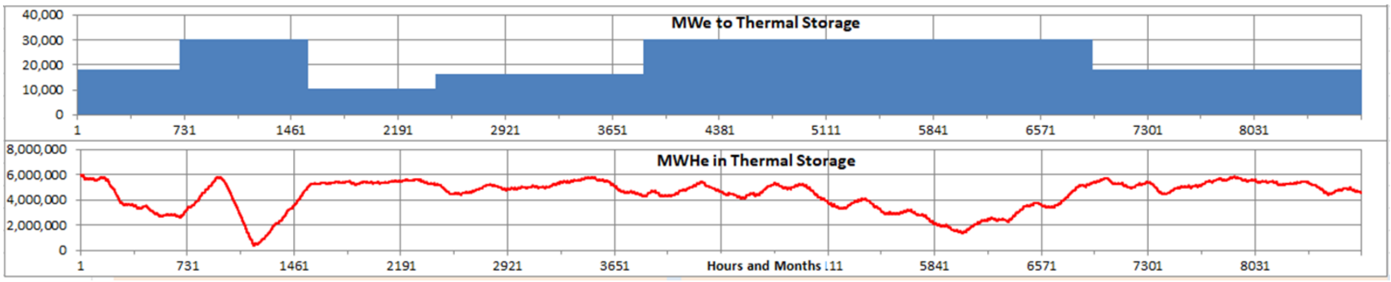

Figure 2. ERCOT22C Thermal Nuclear Seasonal Maintenance and Thermal Storage Energy Versus Hour of the Year

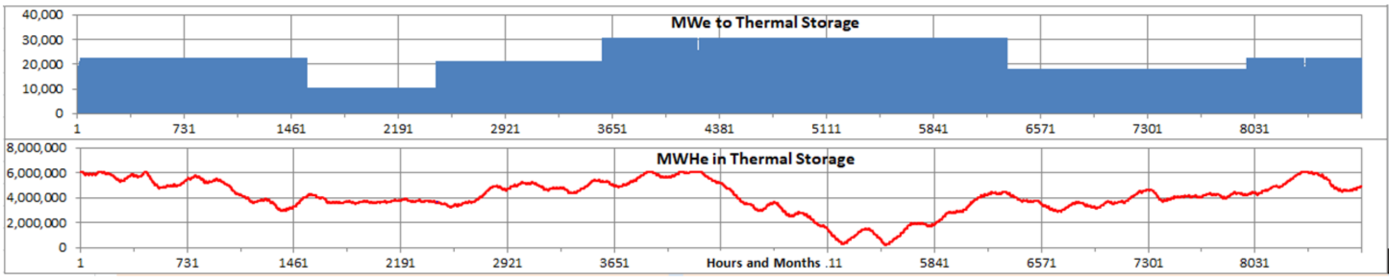

Figure 3. ERCOT22C1 Thermal Nuclear Seasonal Maintenance and Thermal Storage Energy Versus Hour of the Year

V. Unit Capital and Operating Costs

Capital costs and O&M costs are from Alex Pavlak's web site [10]. He has developed a table specifically for entering cost data and other assumptions into these spreadsheet models [11].

Table 1. Unit Costs Given in Reference 11

UNIT COSTS FOR SYSTEM ANALYSIS								
2020 base year Technology	capital recovery period	CAPEX		Capital recovery factor (CRF,real)	capacity factor	Round trip efficiency	fixed O&M	Variable O&M + fuel
	years	$/kW	$/kWh	%	%		$/kW/yr	$/MWh
Offshore wind	20	$4,730		8.9%	44.7%		$113	$0
Onshore wind	20	$1,460		8.9%	30.0%		$43	$0
Utility scale PV 1-axis track	30	$1,330		7.4%	21.5%		$23	$0
AP-1000, base load nuclear	60	$7,440		6.4%	92.0%		$146	$10
Thermal nuclear	60	$6,518		6.4%			$146	$10
Combustion turbine natural gas	30	$922		7.4%			$21	$56
Combustion turbine Green H2	30	$922		7.4%			$21	$440
Combined cycle natural gas	30	$1,038		7.4%			$28	$34
Utility scale Li battery	15	$249	$369	10.4%		85%	$43	$0
Hot rocks storage	30	$922	$43	7.4%		85%	$21	$0

CAPEX is the installed cost in $/kW. The capital cost is financed over the number of years shown. The capital recovery factor is the amount of annual cash flow to pay for the capital cost. The fixed and variable O&M costs are entered as input data in these cases.

The Hot Rocks (CRUSH) is a bit more complex to price out than shown in Table 1. Table 2 shows the entries in ERCOT22C.

Table 2. Nuclear Thermal Storage CAPEX Cost and Efficiency

Nuclear Thermal Storage			CAPEX B$				
power	$/kW nucl	6,518	195.5	6,000	GWh	0.06	% loss/day
power	$/kW gen	922	27.7	63.0	GW	150	MWh/hr
energy	$/kWh	15.0	90.0	200.0	Hrs	0.85	efficiency
			313.2	63.0	GWe nucl	350	MWe storage 250x250x20m.

Because the thermal reactor does not have turbines tied to it, the $7440/kW nuclear price in Table 1 is dropped to $6518/kW. The $922/kW is a cost for the turbines. References 1-4 estimate the thermal storage cost to be in the range of $2-$4/kWh thermal or $6-$12/kWh electrical using a 33% conversion efficiency. A more conservative $15/kWh electrical cost for thermal storage is used.

The 6000 GWh thermal storage is assumed to be 85% efficient when charging. A constant shunt loss estimate of 0.06% of its energy per day is 150 MWh/h. The thermal storage performance will be better understood when prototypes are built and tested.

The cases assume a gas fuel cost of $40/MWh. There is also a reserve margin of 10% of the annual peak demand. This is priced in the form of the capital cost of gas peaking generation that sits idle.

VI. Wind and Solar Unused Energy

Table 3 shows 22C wind is fully utilized and solar loses only 2.34% of its max 23.14% capacity factor (CF). Table 4 shows 22C generation copied to 22A (no storage). The unused wind is 12.45% of the 34.46% max CF. Unused solar is 16.06% of its 23.46% max CF.

Table 3. Utilization of Wind and Solar in 22C

Annual Costs					annual	source
	max % CF	act % CF	unused%		cost M$	cent/kWh
OSW	0.00	0.00	0.00		0	0.000
Nuclear	100.00	100.00	0.00		3,549	8.102
Wind	33.56	33.56	0.00		6,572	5.882
Solar	23.14	20.80	2.34		7,042	6.662
Th Nucl	100.00	74.60	%CF Nucl	refs 4,5	25,192	15.103
Th Genr	100.00	30.21	%CF Genr	refs 4,5		
Fossil	100.00	0.00	100.00		0	0.000
Reserve					1,071	0.250
				total	43,426	10.15

Table 4. Utilization of Wind and Solar if 22C Has No Storage

Annual Costs					annual	source
	max %CF	load %CF	batt %CF	unused%	cost M$	cent/kWh
Nuclear	100.00	99.89	0.00	0.11	24,838	8.110
Wind	34.46	22.01	0.00	12.45	6,572	8.971
Solar	23.46	7.40	0.00	16.06	7,042	18.734
Fossil	100.00	5.46		94.54	3,499	24.247
Battery					0	
Reserve					714	4.946
				total	42,665	9.887

Conclusions

Nuclear, when tied to a large thermal storage system rather than directly to the grid, has a unique ability to harmonize and maximize the utilization of wind, solar, and nuclear resources. The thermal storage can replace natural gas peaking generation creating a pathway to fully decarbonize the electric grid. A CRUSH thermal storage demonstration project needs to be built and tested in ERCOT.

A second objective of this paper is to make available open-source Excel spreadsheet designs for testing different ERCOT decarbonization concepts. The storage algorithms have made the analysis possible in Excel. Excel is easy to run compared with more complex probabilistic economic models which may produce results that are hard to verify. The reliance on historical test years to model specific weather events rather than synthetic models lends confidence that a certain weather event is being studied correctly. This spreadsheet program can be widely used and modified by others.

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I wish to thank Dr. Forsberg for suggesting an ERCOT CRUSH model be constructed using the spreadsheet model. This model was developed with the help of Dr. Alex Pavlak and the Future of Energy Initiative group and especially Dr. Tom Rehm's encouragement for a presentation on decarbonization of ERCOT for his seminar October 2023 at the University of Houston [12]. I thank ERCOT for posting the hourly demand, wind, and solar data making this analysis possible. My time with Austin Energy was valuable in building and improving computer models of generation, transmission, and distribution systems.

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Biographies

Eugene G. Preston, PE, PhD, performs studies for wind and solar projects and large system generation reliability studies. Gene retired from Austin Energy in 1998 with 28 years of experience in generation, transmission, and distribution planning. While at Austin Energy he ran Monte Carlo reliability studies and transmission reliability studies for ERCOT. He developed new ways to increase the speed and accuracy of these studies leading to a PhD from the University of Texas at Austin in 1997. His complex programs have been written in higher level languages. The Excel spreadsheet dispatch model is a new analysis tool he recently developed.

Dr. Charles Forsberg is a principal research scientist at MIT. His current research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs), integrated energy systems including nuclear-assisted biofuels and utility-scale 100 GWh heat storage systems using crushed rock. He teaches the fuel cycle and energy systems classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. Earlier he worked for Bechtel Corporation and Exxon.
He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a former Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 13 patents and published over 300 papers.