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A New View of New York's Electric Grid: Hour-by-Hour Analysis Shows Renewables-Focused Plan Is Unworkable Without Extensive Use of Firm Dispatchable Power

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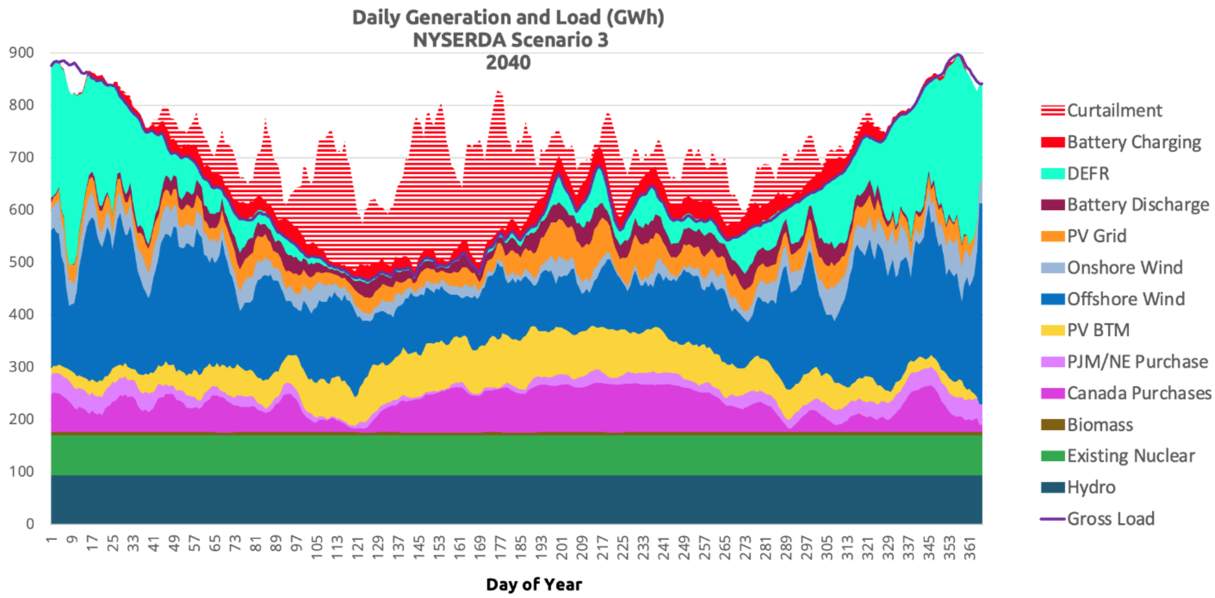
November 2023



Overview

We have analyzed scenarios for decarbonizing New York's electric grid using a new modeling tool that allows an hour-by-hour analysis of grid behavior. This model reveals important features of the grid not disclosed by existing models, including the model used by the New York State Energy Research and Development Authority (NYSERDA). The new model provides extensive quantitative information such as costs to ratepayers and taxpayers, as well as details of the operation of each energy source that NYSERDA's model does not reveal.

Our key finding using this model is that NYSERDA has seriously underestimated the need for large firm dispatchable emission-free resources – ones that are always available and able to supply whatever additional electric load is needed. Due to the expected electrification of automobiles and the heating of buildings, such a resource must operate for more than a third of the year if the State is to have a grid that is reliable and avoids rolling blackouts. Among existing technologies, only nuclear power can meet this need at the scale required by 2040. We show alternate scenarios that will cost much less than the scenarios modeled by NYSERDA, which envision a vast expansion of solar, wind, and storage. This alternate plan uses additional baseload (always-on) nuclear power along with a varying nuclear-powered dispatchable source.

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Introduction: Renewables and the Winter Energy Deficit

The Climate Leadership and Community Protection Act (CLCPA), passed in 2019, mandates that the State's electric grid be free of greenhouse gas emissions by 2040. Responding to that directive, NYSERDA has, over the past two years, modeled four scenarios for the State's Climate Action Council, all of which depend almost entirely on generating electricity from renewable sources.[4,5] The Scoping Plan adopted by the State's Climate Action Council declares that "wind, water, and sunlight will power most of New York's economy." Although the Scoping Plan refers to the possibility of including nuclear power, the quantitative scenario description (the "Integration Analysis") that accompanies the Scoping Plan omits any expansion of nuclear capacity. It retains existing nuclear plants, which meet 20% of today's load, but does not add new ones.[6]

While the focus has been on the renewable sources, the Climate Action Council's Scoping Plan recognizes the need for an additional, dispatchable source: "Plan analysis and current studies show that the 2040 zero-emission goal requires between 15 and 45 gigawatts (GW) of electric power from dispatchable zero-emission resources to meet the demand at that point and maintain reliability".[7] The Scoping Plan does not specify what that source will be, though it does suggest using hydrogen produced with renewable sources as the fuel for such a source.

The following table shows the results NYSERDA presented for its Scenario 3, the most frequently discussed of four possible scenarios.[8] Most remarkably, NYSERDA's model finds that little more than 2% of the potential output of the dispatchable source (labeled "Zero-Carbon Firm Resource") will actually be used. Simple arithmetic makes this seem highly questionable. NYSERDA estimates that, by 2040, building and transportation electrification will have expanded so that the State's electric load will peak in the winter with a maximum load of 46-50 GW.[9] In winter, there is little or no excess solar generating capacity to charge batteries, and in the evenings, of course, there is no solar output. Therefore, excluding imports of power from neighboring states and Canada, which cannot be relied upon, the maximum output in the evenings with both onshore and offshore wind blowing at full capacity will be 30 GW (the average will be just 17 GW).

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[4] https://climate.ny.gov/-/media/project/climate/files/NYS-Climate-Action-Council-Final-Scoping-Plan-2022.pdf

[5] We will use the word "renewable," since it is in widespread common usage. However, it is a misleading term. While the sources of energy, principally the sun and wind, are for practical purposes inexhaustible, the equipment on which they depend has limited lifetimes and must be replaced at least every 20-25 years. Furthermore, most of the materials embodied in them cannot be recycled economically or environmentally responsibly.

[6] At the November 2022 meeting of the Climate Action Council, NYSERDA examined the impact of adding 4 GW of nuclear power to the grid. See https://climate.ny.gov/-/media/project/climate/files/2022-11-07-CAC-Meeting-Presentation.pdf

[7] Page 13. https://climate.ny.gov/-/media/Project/Climate/Files/NYS-Climate-Action-Council-Final-Scoping-Plan-2022.pdf

[8] https://climate.ny.gov/-/media/Project/Climate/Files/IA-Tech-Supplement-Annex-2-Key-Drivers-Outputs.xlsx

[9] ibid.

This leaves a winter time deficit of at least 14 GW and, much of the time, 30 GW or more. To overcome this large deficit on many evenings throughout the winter, a great deal of power will have to be generated by the dispatchable source, or there will be frequent, rolling blackouts. (Including the imports from surrounding areas will not change this conclusion; there is still a large deficit.) Clearly, something is amiss.

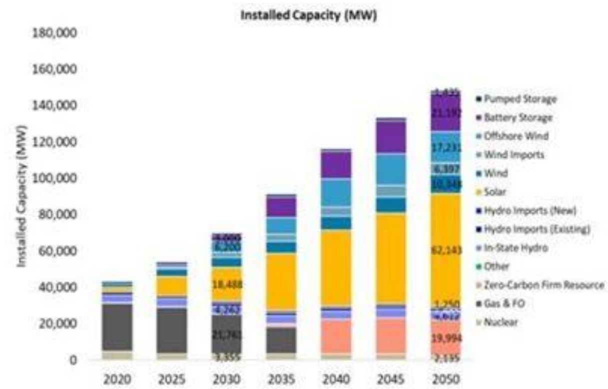
Table 1: NYSERDA Scenario 3

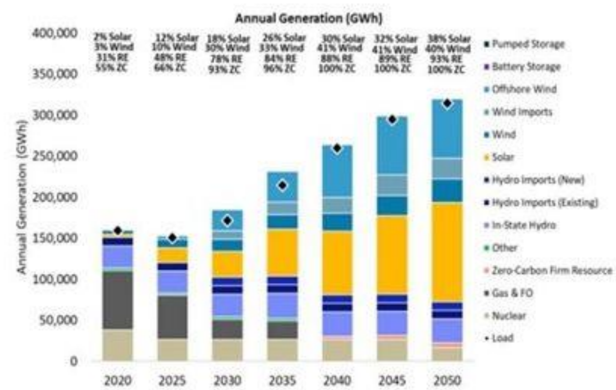
Capacity and Generation Results: Scenario 3

Fuel Mix `	MW	GWh	CF(%)
Nuclear	3,355	26,452	90.0%
Gas & Fuel Oil	-	-	-
Zero-Carbon Firm Resource	23,522	4,440	2.2%
Bioenergy	327	2,721	95.0%
In-State Hydro	4,613	29,982	74.2%
Hydro Imports (Existing)	1,485	10,361	79.6%
Hydro Imports (New)	1,250	8,760	80.0%
Wind	6,126	16,799	31.3%
Wind Imports	6,397	25,002	44.6%
Wind_Offshore	16,756	69,388	47.3%
Solar	41,420	75,966	20.9%
Battery Storage	12,207	(2,443)	-2.3%
Pumped Storage	1,435	(288)	-2.3%
Imports		13,978	
Exports		(13,978)	
Load		267,143	

Note: CF = Capacity Factor = Actual Output/Potential Output

Source: https://climate.ny.gov/-/media/Project/Climate/Files/IA-Tech-Supplement-Annex-2-Key--Drivers-Output.xlsx Updated May 20,2022.





An hour-by-hour analysis of New York's future electric grid

NYSERDA has not explained how it derived its results. The first column in Table 1 shows the rated *capacity* of each source in the plan in megawatts (MW). The calculated electricity *generated* each year in gigawatt-hours (GWh) from each source is shown in the second column. NYSERDA has not disclosed the operational logic that links the output energy (GWh) to the input power (MW). It has disclosed neither the underlying assumptions for resource dispatch to match electric supply with demand, nor what the proposed plan will cost purchasers of electricity and the State's taxpayers. It provides only the output of each source for the entire year.

To fill this critical information gap, we have used a model that performs an hour-by-hour analysis of the projected electricity demand in 2040 to show how the sources assumed in NYSERDA's scenario actually respond to this varying demand. Our grid simulator is the New York adaptation of the model developed for New England by Reiner Kuhr and Ahmad Nofal, experienced energy engineers and leaders at the Center for Academic Collaboration Initiatives (CACI).[10]

The CACI approach uses spreadsheet software to calculate, for each hour throughout the year, how the available energy sources, including battery storage, will be used to meet the projected electric load. In our model, when the non-dispatchable sources – hydro[11], baseload (always-on) nuclear, solar, and wind – are able to meet the load, any excess is used to charge the batteries assumed in this scenario. If they are not able to meet the demand, batteries are called upon to fill the gap. Before 2040, if the electricity from batteries is insufficient, gas-fired plants are called on to cover the residual load; from 2040 on, when the grid is to be emission-free, the model calls upon an as-yet unspecified dispatchable emission-free resource – a DEFR – to meet the remaining load. Appendix A provides a more detailed description of how the CACI model works. To quantify the characteristics of the DEFR in our modeling, we use the parameters of Natrium, a small modular nuclear reactor (SMR) being developed by TerraPower and GE-Hitachi. The Natrium design integrates a 345 MW fast neutron reactor coupled with molten salt thermal storage capable of yielding an output of 500 MW for up to five-and-a-half hours.[12]

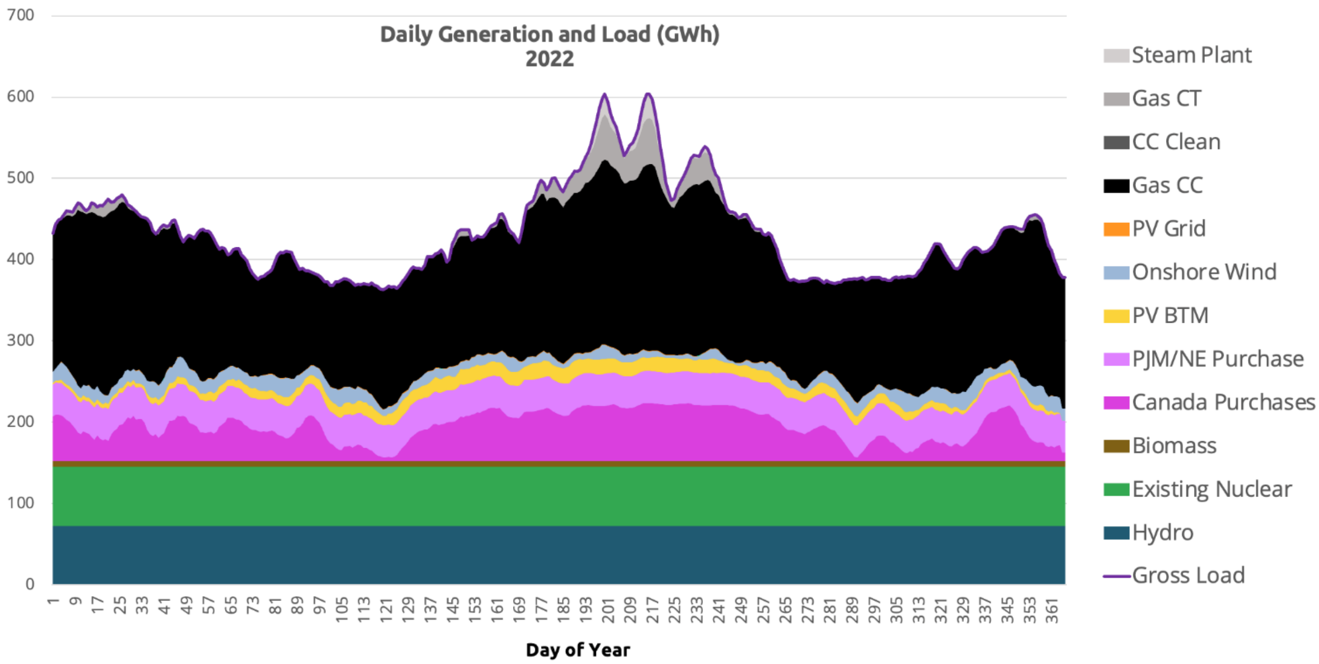
NYSERDA scenarios seriously understate the need for a dispatchable emission-free resource (DEFR)

Our base year is 2022, before large-scale conversion to carbon-free sources has begun. The next figure shows the results of our analysis for every day of 2022. Table B-1 in Appendix B gives detailed quantitative results for this year. Appendix C shows the assumptions made for each of the energy sources, for this year and thereafter. In the figure, one can see the baseload hydro and existing nuclear facilities, the purchase of power from neighboring states and Canada, and finally, the gas- and oil-burning plants meeting the rest of the varying load. Rooftop solar and land-based wind play a minor role.

[10] https://centeraci.com/wp-content/uploads/2022/09/Technical-Economic-Limits-for-Renewable-Power-Integration-in-New-England-Full-Report-Rev-1.pdf

[11] Though hydro is used today to respond to some of the variation in system demand, for simplicity, in this model it is treated as a non-dispatchable resource.

[12] https://natriumpower.com/reactor-technology



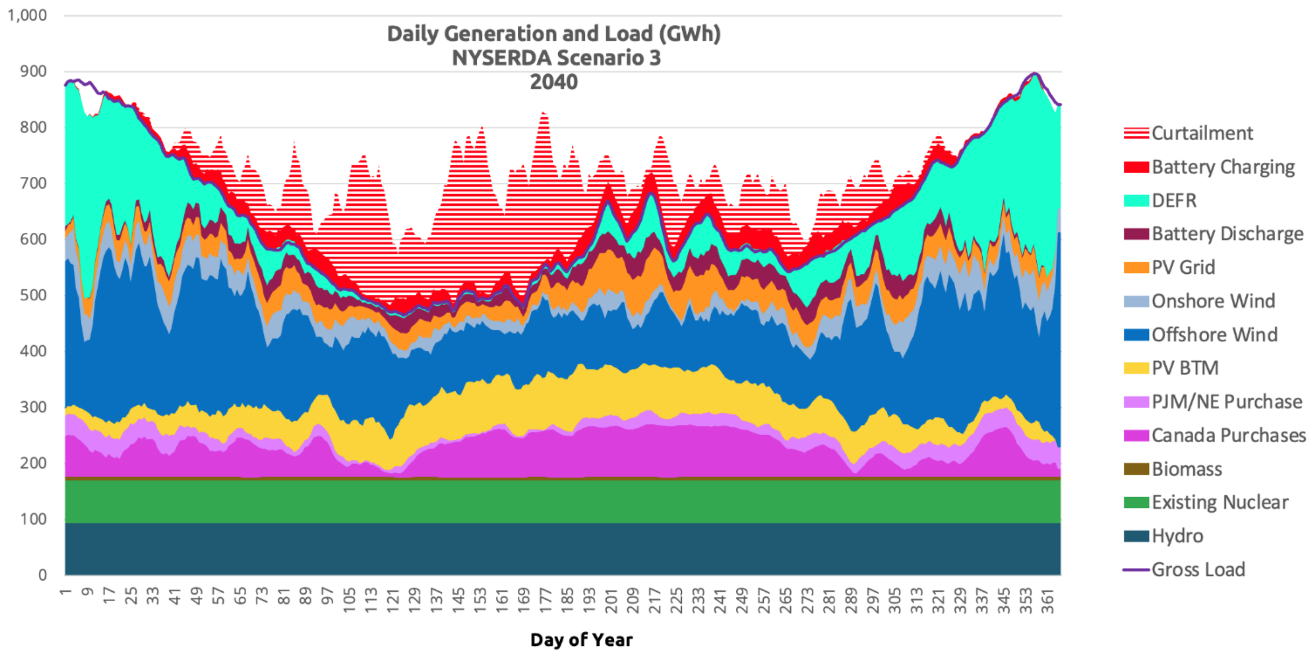
Note: Steam plant – Gas- or oil-fired boilers and steam turbines
Gas CT – natural gas-fired combustion turbines
Gas CC = natural gas-fired combined cycle power plants
PV BTM = Solar photovoltaic behind-the-meter (mostly rooftop solar)
Onshore Wind = Land-based wind power
Offshore Wind = Ocean-based wind power
PJM/NE Purchases = Energy purchased from neighboring states
Canada Purchases = Energy (mainly hydro) purchased from Canada
Biomass = Burning of wood and municipal waste
Hydro = Power plants on Niagara and St. Lawrence Rivers
Existing Nuclear = Power plants on Lake Ontario

Electricity Supply 2022

Source	Capacity MW	Output GWh/yr	Capacity Factor %	% Load
Existing Nuclear	3,305	26,700	92.2%	16.8%
Hydro	4,265	26,487	70.9%	16.6%
PV BTM	3,760	4,360	13.2%	2.7%
PV Grid	154	179	13.2%	0.1%
Onshore Wind	2,191	4,867	25.4%	3.1%
Biomass	258	2,261	100.0%	1.4%
Gas CC	10,843	60,132	63.3%	37.8%
Gas CT	4,186	2,577	7.0%	1.6%
Steam Plants	10,637	539	0.6%	0.3%
NE and PJM Purchases		14,401		9.0%
Canada Purchases		16,090		10.1%
Load		159,186		100.0%

Total Generation Cost: $88 per megawatt-hour (MWh)

The table and figure below describe 2040 grid behavior under NYSERDA Scenario 3, when all electricity is to be emission-free. These show the contribution of each energy source in meeting the electric load for from January 1 to December 31 2040. In 2025, the available capacity from Canada increases by 1,250 MW, to account for the Champlain Hudson Power Express (CHPE), presently under development.[13]

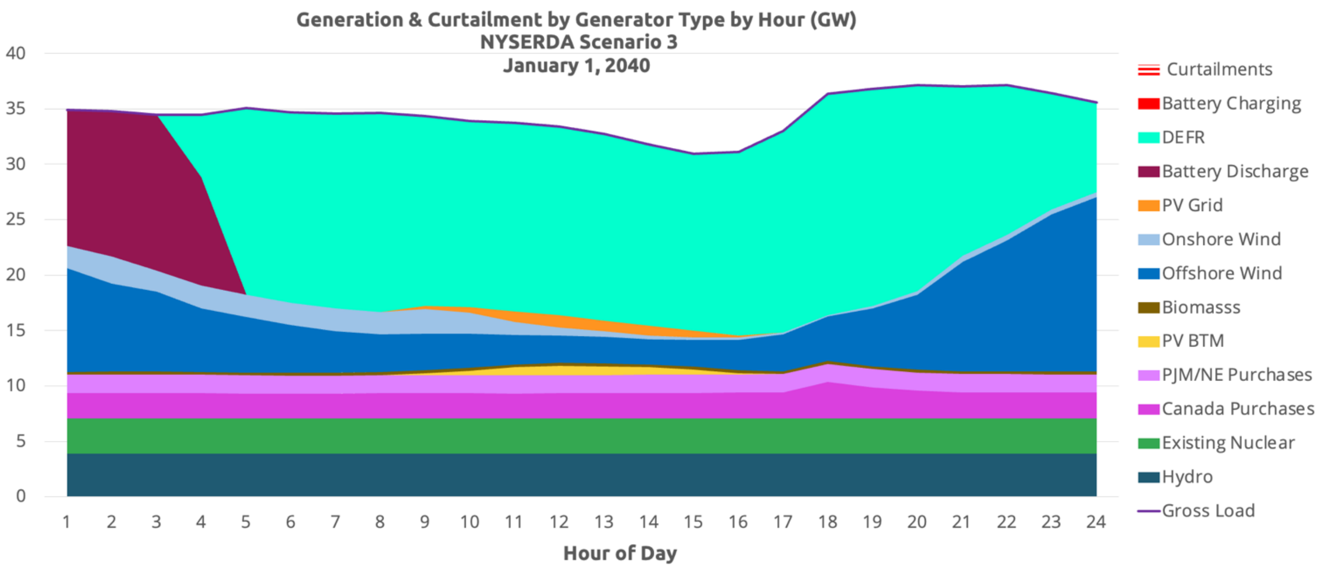


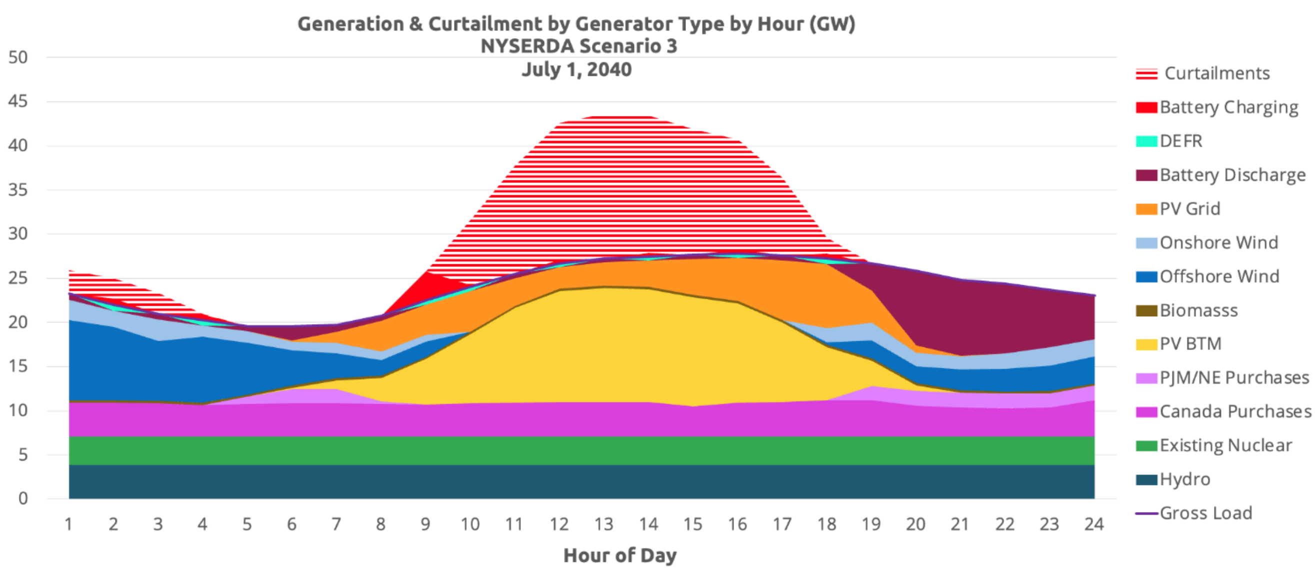
Electricity Generation NYSERDA Scenario 3 2040				
Source	**Capacity MW**	**Output GWh/yr**	**Capacity Factor %**	**% Load**
Existing Nuclear	3,458	27,936	92.2%	11.6%
Hydro	5,485	34,037	70.8%	14.2%
PV BTM	18,532	21,489	13.2%	8.9%
PV Grid	24,013	16,706	7.9%	6.9%
Onshore Wind	6,435	11,972	21.2%	5.0%
Offshore Wind	17,535	60,301	39.3%	25.1%
Biomass	258	2,247	99.4%	0.9%
Batteries Discharging	12,306	7,665	7.1%	3.2%
DEFR	23,500	29,707	14.4%	12.4%
NE and PJM Purchases		7,393		3.1%
Canada Purchases		21,080		8.8%
Load		240,532		100.0%

Total Generation Cost: $257/MWh

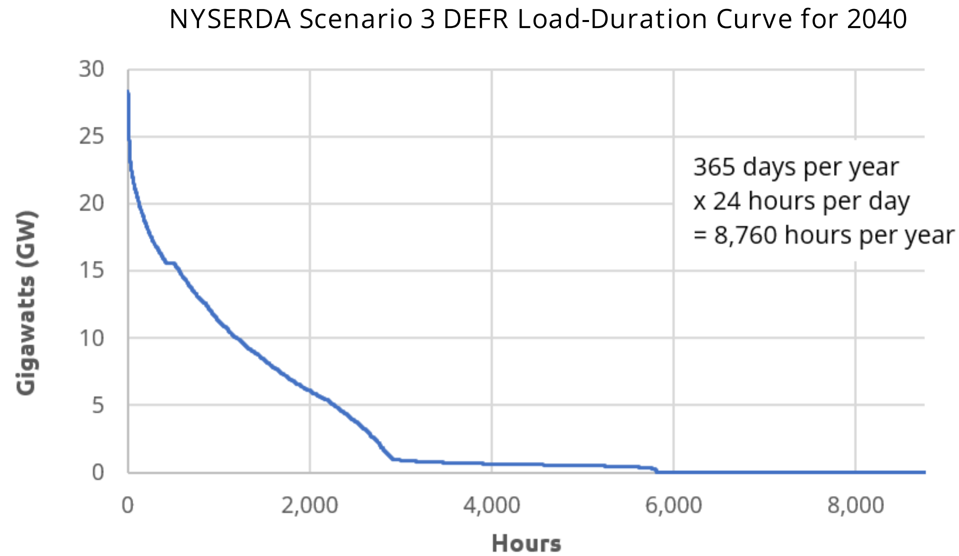
[13] CHPE capacity is modeled as uniformly available throughout the year, when NYISO has warned of its unavailability during the winter, as the facility is not obligated to provide any capacity in the winter per the contract terms. https://www.nyiso.com/-/press-release-%7C-nyiso-report-highlights-risks-to-future-grid-reliability

The charts below visualize how the hourly electricity load is met, midnight to midnight for a mid-winter day (January 1) and a mid-summer day (July 1). Detailed quantitative results for this scenario are given in Table B-2 in in Appendix B.





These visualizations tell a striking story. The 2040 total load (250,532 GWh) has increased substantially from 2022 (159,186 GWh). The 2022 summer peak, largely reflecting air conditioning, has been replaced in 2040 by a much higher winter peak. This is largely the result of the planned electrification of building heating and transportation. The heating load is greatest in the winter, and that greater demand is met by the extended operation of the DEFR, the as-yet unspecified controllable source. The chart in the previous page demonstrates how DEFR is used extensively during most days in the cooler portion of the year. Instead of using just a small portion of its potential annual output, as NYSERDA's model suggests, we find that 14% of its potential annual output will be needed – the equivalent of operating one full day every week. (There is also an unmet load of about 10 GW, a partial blackout for a few days in the mid-winter period, early in January.) The load-duration curve shows the number of hours each level of output is required from the DEFR. Most of its output is used during one-third of the year, mostly in the winter; a smaller amount (less than 1 GW) is needed for another third of the hours, mostly in the evenings.



The demand for electricity by 2040 is so great that, even with what NYISO, New York's grid operator, has described as an "unprecedented"[14] expansion of solar and wind, these renewable sources are unable to meet the demand. Solar, of course, is not available at night, so the DEFR generators have to be fired up nearly every day of the year. This is shown clearly for January 1 in on page 7. The batteries are charged up during many days, but they discharge and are drained early in the evening, and then the DEFR has to take over to keep power on throughout the night.[15]

At night, when solar is not available, the grid is dependent on hydro, nuclear, wind, and the DEFR to keep the lights on. The available output in the evening is about 8 GW from hydro and existing nuclear, along with a maximum of 22 GW from the assumed wind resource. NYSERDA projects that the peak demand in a winter evening will be between 46 and 50 GW, so the DEFR has to supply, nearly every night, at least 14 GW, and often much more.

Battery storage helps for a few hours in the evening, if it has been charged during the day, but the DEFR has to take over on most nights. The extensive use of the DEFR that we have found conflicts with the

[14] https://www.nyiso.com/documents/20142/2223020/2023-Power-Trends.pdf/

[15] For convenience, we arbitrarily assume the batteries start the year fully charged. That is unlikely to happen normally, since there will be little excess capacity to charge them on a mid-winter day.

results of NYSERDA's analysis. NYSERDA found that the DEFR had to be used only a few days each year, while we find that it has to run at least a third of the year and carry a substantial portion of the load.

The overbuilding of solar and wind energy is wasteful, leading to very expensive electricity.

Another unexpected finding is how small a fraction the grid-connected solar output is actually usable. Its operational capacity factor – the actual electricity delivered to the grid over the year compared to its maximum potential output – is just 7.9%. The grid-connected solar units could produce nearly twice that amount, but much of that output is not needed during the day when it is produced and, when not needed to charge the batteries, is discarded.

Above the total load line are the "curtailments", the excess solar and wind whose output at any time exceeds the demand and has to be discarded. Wasteful curtailment occurs on a large scale throughout the year but, most clearly, in the summer months.

The ineffective use of solar revealed by our analysis reflects significant overbuilding of solar and will be a vast waste of money. Solar's output peaks every day at a time when the demand is relatively low. Overall, the model shows that 31% of the total output from grid-connected renewables is not delivered to customers. Behind-the-meter (rooftop) solar is fully used because NYISO, does not control it and cannot turn it off. However, NYISO does control the grid-connected solar and wind and has to curtail output that is not needed.

Because of this wasteful overbuilding of renewables, the cost of electric generation in 2040 under NYSERDA's scenario is more than double what it is today. In 2022, we found the wholesale cost of electricity to be $88 per MWh, However, by 2040 it rises, in NYSERDA's scenario in constant dollars (i.e., excluding the effect of general inflation), to $257 per MWh.[16] Table B-1 shows a detailed breakdown of these costs.

A far less costly plan is possible using nuclear power

NYSERDA did not consider nuclear energy to be a "candidate resource" in its analysis. However, it acknowledged, in its November 2022 presentation to the Climate Action Council, that adding 4 GW of

[16] Note that this estimate does not include the cost of expanding the transmission network that would be needed to connect the thousands of solar and wind facilities that would be built in NYSERDA's scenario. For reference, the Champlain Hudson Power Express, a 1,250 MW transmission line to bring hydro-power from Quebec to New York City is to cost $6 billion dollars, while Clean Path New York, a 178-mile 330-mile 1,300 MW project that promises to deliver solar and wind from Delhi, NY to Queens, NY is to cost $11 billion dollars. Furthermore, the model uses 2020 costs and does not include recent substantial cost increases. (Cost assumptions are shown in Appendix C.)

nuclear would save money, material resources, and land.[17] In fact, NYSERDA estimated that 4 GW of nuclear could avoid the need for 12 GW of intermittent generation and 5 GW of storage and backup generation. When producing heat or electric power, nuclear reactors emit no greenhouse gases. They are reliable, capable of producing power round the clock regardless of the weather. Nuclear supplied 27% of the State's electric power, on average since 1993, and was responsible for 57% of carbon-free generation during this period.[18]

It turns out that Energy + Environmental Economics, Inc. (E3), the San Francisco-based consulting firm which performed the analysis for NYSERDA, is familiar with the role that nuclear can play in meeting a large and varying load. In fact, in an earlier study of decarbonization in the Pacific Northwest, E3 found an important role for small modular nuclear reactors (SMRs), observing that "…achieving 100% GHG reductions using only wind, solar, hydro, and energy storage is both impractical and prohibitively expensive."[19] Nevertheless, no new nuclear was included in NYSERDA's analysis accompanying the Scoping Plan.

When we recognize the potential role that nuclear power can play and incorporate it into the State's future grid, we can create a plan that will reliably keep the lights on and be much more affordable than the scenarios that have been considered to date. We highlight here two scenarios of a future energy system which can successfully achieve New York's climate goals at a much lower cost.

The following alternative scenarios, which we term "Brighter Future," build upon a 2022 policy proposal prepared by Nuclear New York, Clean Energy Jobs Coalition NY, and A Campaign for a Green Nuclear Deal.[20] Recognizing that much of New York's electricity demand is constant throughout the year, Brighter Future utilizes nuclear power as a principal source of clean power throughout the year, not simply as a DEFR when solar and wind are incapable of meeting the load. Nuclear becomes the *backbone* of the system, not simply a *backup* to intermittent, weather-dependent renewables.

These scenarios include 7 GW of new baseload nuclear power – adding more than twice what is already operating in upstate New York – along with 24 or 27 GW of variable, dispatchable emission-free nuclear power – a DEFR. Far fewer solar and wind installations are needed. Our grid model presently does not use DEFR to charge batteries. Hence adding batteries add costs but are seldom charged. The Brighter Future scenarios here exclude batteries, but we aim to evaluate their inclusion in future research. The first,

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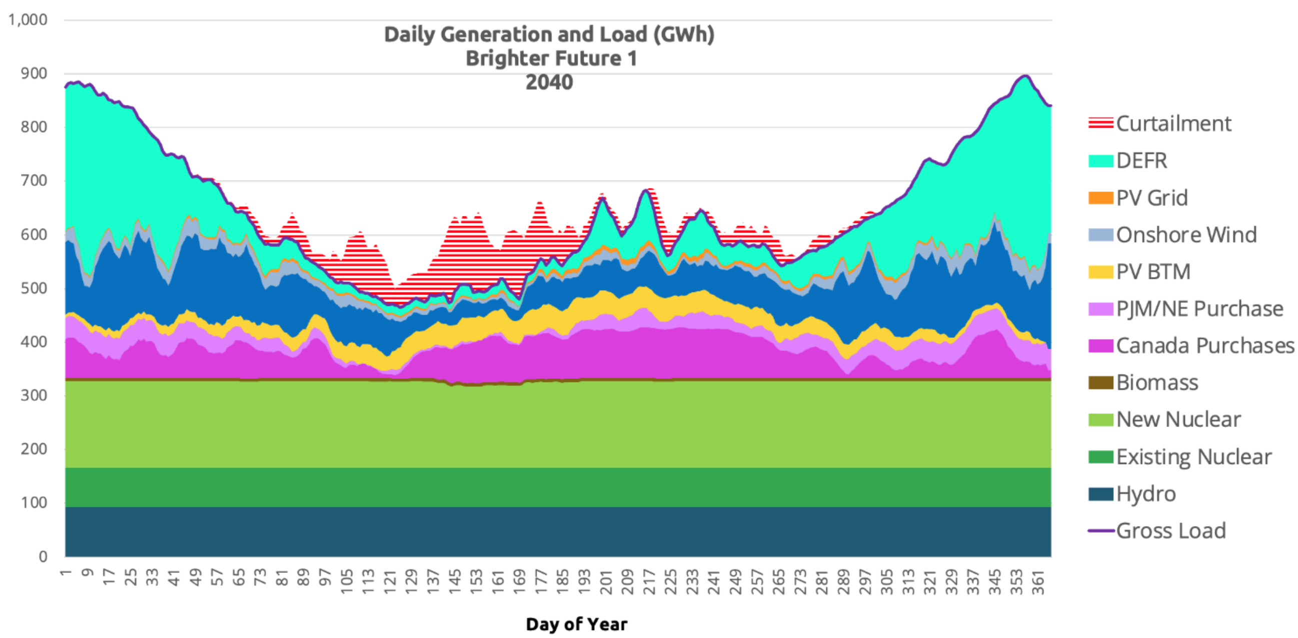
[17] https://climate.ny.gov/-/media/project/climate/files/2022-11-07-CAC-Meeting-Presentation.pdf

[18] https://data.ny.gov/Energy-Environment/Electric-Generation-By-Fuel-Type-GWh-Beginning-196/h4gs-8qnu

[19] https://www.ethree.com/wp-content/uploads/2019/03/E3_Resource_Adequacy_in_the_Pacific-Northwest_March_2019.pdf

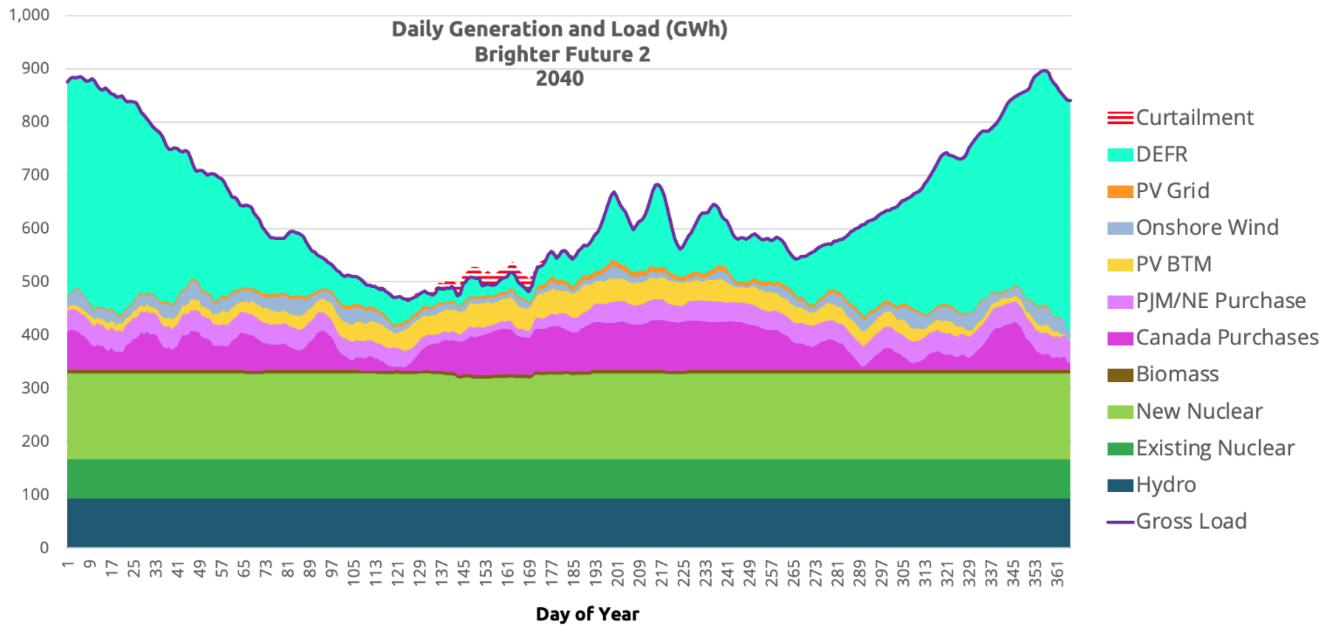
[20] https://www.nuclearny.org/bright-future/

Brighter Future 1, has 9 GW of offshore wind, the minimum called for in the CLCPA. Bright Future 2 has no offshore wind and costs significantly less than the scenario with offshore wind. Not only does offshore wind add to the system cost, but it is vulnerable to shutdown and even serious damage when frequent and increasingly intense storms arrive from the Atlantic.[21]



Electricity Generation Brighter Future 1 2040				
Source	**Capacity MW**	**Output GWh/yr**	**Capacity Factor %**	**% Load**
Existing Nuclear	3,305	26,700	92.2%	11.4%
New Nuclear	7,000	58,579	95.5%	25.1%
Hydro	5,485	34,037	70.8%	14.6%
PV BTM	9,000	10,436	13.2%	4.5%
PV Grid	2,050	1,670	9.3%	0.7%
Onshore Wind	3,039	5,669	21.3%	2.4%
Offshore Wind	9,000	29,665	37.6%	12.7%
Biomass	258	2,261	100.0%	1.0%
DEFR	24,000	34,656	16.5%	14.8%
NE and PJM Purchases		8,665		3.7%
Canada Purchases		21,080		9.0%
Load		233,418		100.0%
Total Generation Cost $166/MWh				

[21] Will New York City Survive the State's Energy Plan? Testimony before the NYC City Council Committee on Environmental Protection, 2020. https://www.dropbox.com/s/e2g9af0pefiulm2/Will%20NYC%20Survive%20the%20State%27s%20Energy%20Plan%20-%20Testimony%20of%20Leonard%20Rodberg.pdf?dl=0



Electricity Generation Brighter Future 2 2040				
Source	**Capacity MW**	**Output GWh/yr**	**Capacity Factor %**	**% Load**
Existing Nuclear	3,305	26,700	92.2%	11.4%
New Nuclear	7,000	58,579	95.5%	25.1%
Hydro	5,485	34,037	70.8%	14.6%
PV BTM	9,000	10,436	13.2%	4.5%
PV Grid	2,050	2,041	11.4%	0.9%
Onshore Wind	3,039	6,438	24.2%	2.8%
Biomass	258	2,261	100.0%	1.0%
DEFR	27,000	59,259	25.1%	25.4%
NE and PJM Purchases		12,572		5.4%
Canada Purchases		21,080		9.0%
Load		233,404		100.0%
Total Generation Cost $154/MWh				

Nuclear plants require just a few acres of land and have negligible impact on the surrounding physical environment.[22] Comprehensive lifecycle analysis by the United Nations Economic Commission for Europe shows that, compared with other energy technologies, nuclear power has substantially lower ecosystem impacts when considering climate change, land use, and human health.[23] Most importantly, even before accounting for transmission expansion costs, or the nuclear capital cost reductions likely to

[22] https://ourworldindata.org/land-use-per-energy-source

[23] https://unece.org/sed/documents/2021/10/reports/life-cycle-assessment-electricity-generation-options

occur as plants are deployed across the U.S., the Brighter Future scenarios cost only 60-71% of NYSERDA Scenario 3.

The below table summarizes our findings, and provides total per-unit generation costs under two DEFR capital cost scenarios: low-cost at ~$6,000/kW and high-cost at ~$12,000/kW.

2040 Scenarios	DEFR Requirement (GW)	DEFR Capacity Utilization	Total Generation Cost ($/MWh)	
			Low-Cost DEF (~$6,000/kW)	High-Cost DEFR (~$12,000/kW)
NYSERDA Scenario 3	23.5	14.3%	$257	$304
Brighter Future 1	24.0	16.5%	$166	$216
Brighter Future 2	27.0	25.1%	$154	$196

It should be noted that the data in our model use current estimated capital costs for new nuclear facilities, $10,000/kW for new gigawatt-scale plants, and $6,000/kW for load-following small modular reactors (SMRs). The electricity costs in the Brighter Future scenarios could be substantially lower as multiple successive installations bring nuclear plant costs down, as South Korea, France, Japan, and others have demonstrated (e.g., South Korea has installed large plants for $2,500/kW). An independent assessment by the Massachusetts Institute of Technology's Center for Advanced Nuclear Energy Systems in March 2022 expected overnight capital cost of the next gigawatt-scale plant in the U.S. to be $4,300/kW.[24]

A large dispatchable emission-free resource is essential. What should it be?

Our results show that any plan for decarbonization requires a large-capacity dispatchable emission-free resource running a significant part of the year. What can it be? What can power it?

A number of suggestions have been offered:

- Hydrogen: Hydrogen fuel cells or combustion power plants similar to those now burning fossil fuels could run on "green hydrogen" produced through hydrolysis from renewable energy, as NYSERDA has suggested. However, it requires not only the creation of an expensive infrastructure to transport and store the hydrogen, but also a large buildout of additional costly, land-hungry solar and wind facilities to power the hydrolysis plants that produce the hydrogen. (These costs are not included in our estimates.) Using hydrogen for energy storage is challenged by the fact that the round-trip power-to-gas-to-power (P2G2P) efficiency is 40%.[25] This means more than twice the amount of usable energy needs to be generated, with a commensurate drain on resources, land,

[24] The analysis was specific to Westinghouse's AP1000, a design with fully completed detailed specifications, real-world in-country operating experience, a ready construction workforce, and regulatory familiarity. https://web.mit.edu/kshirvan/www/research/ANP193%20TR%20CANES.pdf

[25] https://www.sciencedirect.com/science/article/pii/S1040619021001330

and societal wealth.

- Long-duration storage: This might help, but currently no realistic scalable form of such storage exists. If it did, it, too, would require a vast expansion of solar and wind power to charge whatever storage medium is used.
- Carbon capture and storage (CCS) attached to gas-fired power plants: This only exists on an experimental basis. It would add substantial cost to the power it was attached to, and there would be upstream leakage of greenhouse gases and other pollutants to the environment. The captured CO_2 would have to be disposed of, presumably underground, adding additional cost as well as potential environmental damage.
- Nuclear power: This is what the model used in the computations here. No other source can be available affordably by 2040 in the quantity required. Only nuclear power has already been demonstrated to have the necessary capabilities, not only in the gigawatt-scale reactors now operating in New York State and elsewhere, but in the smaller reactors operating on submarines and ships for over fifty years (many designed for the U.S. Navy at the Knolls Atomic Power Laboratory in Niskayuna, NY). A variety of large and small reactors are in development nationwide and will be available within the next few years.
- Nuclear-generated fuels: When New York decides that it will accept new nuclear facilities as part of its energy future, then alternative ways of using nuclear energy will deserve consideration. Nuclear reactors are most efficient when they run continuously. We found that the DEFR would be operating at partial capacity for most of the year. A more cost-effective plan might use a smaller number of reactors running continuously to produce hydrogen which could be burned in existing gas- and oil-burning plants, suitably converted to burn hydrogen. Another option would be to use nuclear facilities to produce carbon-neutral synthetic fuels.[26,27] Full analysis of the cost and suitability of these options is beyond the scope of this paper, but they deserve serious study.

[26] Operational Energy from Seawater, US Naval Research Laboratory. https://www.hydrogen.energy.gov/pdfs/review18/ia018_willauer_2018_p.pdf

[27] https://www.ans.org/news/article-4606/nuclear-energy-enabling-production-of-food-fiber-hydrocarbon-biofuels-and-negative-carbon-emissions/

Conclusion

We have shown, with an hour-by-hour examination of a scenario prepared by NYSERDA, that a plan predominantly reliant on intermittent renewable generation will require a large dispatchable source of clean power that runs far more than NYSERDA anticipates. The only such source likely to be available within the next several decades to accomplish this is nuclear power. The State will further benefit from the construction of additional baseload nuclear facilities. This combination of nuclear resources will be far more cost-efficient and environmentally-protective than any other alternative. The State needs to get moving on it now.

Appendix A: CACI Grid Model Methodology

The New York adaptation of the CACI Grid Model works as follows:

In this model, each type of energy source is dispatched hourly to address electric loads, taking account of inter-regional power purchases and sales. CO_2 emissions (if any), wholesale energy pricing, and the occurrence of surplus energy each hour from excessive non-dispatchable generation is also calculated.

Model inputs include hourly data for loads, solar generation, wind generation, hydro generation, and power exchange with other regions. The assumptions and methods used in the model are as follows:

Power generation is represented in these simplified categories: behind the meter (BTM) and grid-connected solar, onshore and offshore wind, hydroelectric, nuclear, battery storage, and a series of possible dispatchable sources. For earlier years, when the burning of fossil fuels is permitted, gas-fired combined-cycle and simple-cycle plants are included. Existing nameplate capacities are taken from NYISO publications, while actual output is based on 2022 NYISO data.

Total system loads are estimated using 2022 data from New York Independent System Operator (NYISO), which operates the State's electric grid.[28] Projections of current demand, as well as the new demand from electric vehicles (EVs) and the electrification of buildings, are drawn from those developed by NYISO and the New York State Energy Research and Development Authority (NYSERDA).[29]

Hourly generation from solar and onshore and offshore wind is scaled up based on the distribution of 2022 hourly output data for these sources, and offshore wind uses 2021 hourly net capacity factors provided by NYISO.[30,31] Hourly load shapes are estimated by reviewing hourly data for weekend/holidays and weekdays. Maximum and minimum daily loads are adjusted weekly based on historic data to account for seasonal variation and adjusted annually based on load growth projected by NYISO. Purchases from Canada and PJM-NE are modeled based on 2022 actual hourly data.

Capacity factors – the fraction of the potential output of a source that is actually produced during the year – is not assumed but are calculated by the model, based upon the weather and the behavior of the grid.

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[28] NYISO Open Access Same-Time Information System http://mis.nyiso.com/public/

[29] EV and Building Electricity Table I-1d, 2022 NYISO Gold Book https://www.nyiso.com/gold-book-resources

[30] NYISO Offshore Wind Profile Development – Summary. February 07, 2023. https://www.nyiso.com/documents/20142/36079056/4%2023_02_07_ICAPWG_OffshoreWindProfileDevelopment.pdf/a982dbb7-b1f3-cee0-ed21-b1f5e3d54539

[31] https://www.nyiso.com/documents/20142/36079056/4%20NYISO_OffshoreWind_Hourly_NetCapacityFactor.xlsx/dc15cb6a-b6fc-6a6a-e1d0-467d5c964079

The Zero-emission Firm Resource utilized in the NYSERDA's scenarios – referred to in this paper by the acronym DEFR (Dispatchable Emission-Free Resource) – is modeled using the characteristics of the TerraPower Natrium small modular reactor.[32]

Battery storage is modeled by assuming the batteries are charged when there is more inflexible power from hydropower, nuclear, grid-connected solar, and wind than is needed to meet demand. The DEFR is not used to charge batteries. The batteries are discharged when the load on the grid is greater than can be provided by those ongoing inflexible sources.

Hourly loads and source dispatch are determined for each day of the year. Hourly load patterns are modeled based on 2022 data available from NYISO. Hourly load shapes are selected for workdays and for non-work holiday/weekend days and adjusted weekly for seasonal changes. NYISO reports estimated generation from behind-the-meter solar, even though it occurs on the customer side of the grid. Behind-the-meter solar currently represents the majority of solar electric generation capacity, but that will change as State plans proceed.

Each source is dispatched in turn to meet the load, as follows: behind-the-meter solar is introduced first, leaving the remaining load to be served by the various sources connected to the grid. Purchases from the neighboring states and Canada are added. Existing nuclear plant output is added as "must-run" capacity. Hydroelectric generation is added, and output from biomass sources (wood, municipal solid waste, and landfill gas) are likewise added. Output from grid- connected solar plus onshore and offshore wind generation are then added, taking into account their hourly variations as described above.

Three percent of the maximum annual load is set aside for system control by gas combined-cycle plants or battery discharge, representing spinning reserve and other ancillary grid services. This is required even when there are curtailments of solar and wind generation.

When there is unmet load remaining after these non-dispatchable sources have been included, the batteries are called on to discharge up to their ability. If unmet load still remains, then the DEFR is used to supply the remaining load.

Curtailments occur when total non-dispatchable generation exceeds the load requirements. When there is insufficient load to use all possible solar and wind generation, purchases from Canada and PJM/NE are reduced or eliminated. Then curtailments are assigned in random order to offshore wind, onshore wind, and grid-connected solar, but not to BTM solar, which is not controlled by the grid operator.

[32] https://www.terrapower.com/our-work/natriumpower/

The model uses current dollars so that the effects of future inflation do not confuse the analysis. Costs of energy sources are estimated from a variety of data sources. The prices used in the scenarios reported here are shown in Appendix C. The total native generation cost of electricity is the weighted average of annual generation sources. The cost for each generation source includes fixed and variable operation and maintenance (O&M) cost, fuel cost, and capital recovery.

We are not reporting energy generator revenues as we have not analyzed the breakdown between energy market income vs. revenue from capacity and ancillary service auctions operated by NYISO. The actual revenue sources depend upon varying arrangements for tax subsidies and other mechanisms for shifting costs from, and among, ratepayers, so this data would be too uncertain to be meaningful.

Appendix B: Data Sheets

Table B-1: 2022 Electricity Generation and Costs

Generation Summary						2022				
Non-dispatchable	**Capacity** MW	**Generation** GWh/yr	**Capacity Factor** %	**% Total Load**	**Capital Cost** $/kW	**Fixed O&M** $/MWh	**Variable O&M** $/MWh	**Fuel Cost** $/MWh	**Capital Recovery** $/MWh	**Native Generation Cost** $/MWh
Existing Nuclear	3,305	26,700	92.2%	16.8%	$141	$28.61	$1.22	$4.09	$2.84	$36.75
Hydro	4,265	26,466	70.8%	16.7%		$7.06	$1.48	-	-	$8.54
PV BTM	3,760	4,360	13.2%	2.7%	$4,647	$17.25	-	-	$720.81	$738.06
PV Grid	154	179	13.2%	0.1%	$1,281	$13.75	-	-	$198.64	$212.39
Onshore Wind	2,191	4,861	25.3%	3.1%	$2,701	$12.43	-	-	$218.97	$231.40
Biomass	258	2,261	100.1%	1.4%		$15.02	$5.06	-	-	$20.08
Sub Total	13,933	64,828	53.1%	40.8%		$17.32	$1.28	$1.68	$66.61	$86.90

Dispatchable	**Capacity** MW	**Generation** GWh/yr	**Capacity Factor** %	**% Total Load**	**Capital Cost** $/kW	**Fixed O&M** $/MWh	**Variable O&M** $/MWh	**Fuel Cost** $/MWh	**Capital Recovery** $/MWh	**Native Generation Cost** $/MWh
Gas CC	10,843	60,293	63.5%	38.0%	$1,485	$2.30	$1.96	$31.53	$44.35	$80.14
Gas CT	4,186	2,577	7.0%	1.6%	$979	$11.91	$4.71	$49.03	$228.82	$294.47
Steam Plants	10,637	539	0.6%	0.3%		$2.30	$1.96	$31.53	$44.35	$80.14
Sub Total	25,666	63,409	28.2%	39.9%		$92.66	$2.07	$32.24	$51.85	$88.85
Native Generation		128,237								$87.86

Regional purchases	Purchased GWh/yr	% Total Load		Total GWh	% Total Load
NE and PJM Purchases	14,401	9.1%	Curtailments	0	0.0%
Canada Purchases	16,086	10.1%	Unmet Load	0	0.0%
Sub Total	30,487	19.2%			
Total	158,724	100.0%			

Note: O&M Operation and Maintenance

Steam Plants are ascribed the same economics of Gas CC plants.

Table B-2: NYSERDA Scenario 3 Generation and Costs (2040)
at $5,988/kW DEFR capital cost

Generation Summary					NYSERDA Scenario 3 (2040)					
Non-dispatchable	**Capacity** MW	**Generation** GWh/yr	**Capacity Factor** %	**% Total Load**	**Capital Cost** $/kW	**Fixed O&M** $/MWh	**Variable O&M** $/MWh	**Fuel Cost** $/MWh	**Capital Recovery** $/MWh	**Native Generation Cost** $/MWh
Existing Nuclear	3,458	27,936	92.2%	11.6%	$141	$28.61	$1.22	$4.09	$2.84	$36.75
Hydro	5,485	34,037	70.8%	14.2%		$7.06	$1.48	-	-	$8.54
PV BTM	18,532	21,489	13.2%	8.9%	$4,647	$17.25	-	-	$720.81	$738.06
PV Grid	24,013	16,706	7.9%	6.9%	$1,281	$22.92	-	-	$331.08	$354.00
Onshore Wind	6,435	11,972	21.2%	5.0%	$2,701	$14.82	-	-	$261.14	$275.96
Offshore Wind	17,535	60,301	39.3%	25.1%	$8,588	$33.49	$0.01	-	$210.49	$243.98
Biomass	258	2,247	99.4%	0.9%		$15.11	$5.06	-	-	$20.17
Sub Total	75,716	174,687	26.3%	72.6%		$23.03	$0.55	$0.65	$211.34	$235.58

Dispatchable	**Capacity** MW	**Generation** GWh/yr	**Capacity Factor** %	**% Total Load**	**Capital Cost** $/kW	**Fixed O&M** $/MWh	**Variable O&M** $/MWh	**Fuel Cost** $/MWh	**Capital Recovery** $/MWh	**Native Generation Cost** $/MWh
Battery Discharge	12,306	7,665	7.1%	3.2%	$1,387	$41.68	-	-	$389.25	$430.93
DEFR	23,500	29,707	14.4%	12.4%	$5,988	$90.54	$3.14	$4.61	$242.22	$340.51
Sub Total	35,806	37,372	11.9%	15.5%	-	$109.66	$2.50	$3.67	$272.37	$359.06
Native Generation		212,059								$257.34

Regional purchases	Purchased GWh/yr	% Total Load		Total GWh	% Total Load
NE and PJM Purchases	7,393	3.1%	Curtailments	27,659	11.5%
Canada Purchases	21,080	8.8%	Unmet Load	545	0.2%
Sub Total	28,473	11.9%			
Total	240,532	100.0%			

Table B-3-1: Brighter Future 1 Generation and Costs (2040)
at $5,988/kW DEFR capital cost

Generation Summary				Brighter Future 1 (2040)						
Non-dispatchable	**Capacity** MW	**Generation** GWh/yr	**Capacity Factor** %	**% Total Load**	**Capital Cost** $/kW	**Fixed O&M** $/MWh	**Variable O&M** $/MWh	**Fuel Cost** $/MWh	**Capital Recovery** $/MWh	**Native Generation Cost** $/MWh
Existing Nuclear	3,305	26,700	92.2%	6.1%	$141	$28.61	$1.22	$4.09	$2.84	$36.75
New Nuclear	7,000	58,579	95.5%	13.4%	$9,992	$15.22	$2.48	$4.10	$61.06	$82.85
Hydro	5,485	34,037	70.8%	7.8%		$7.06	$1.48	-	-	$8.54
PV BTM	9,000	10,436	13.2%	2.4%	$4,647	$17.25	-	-	$720.81	$738.06
PV Grid	2,050	1,670	9.3%	0.4%	$1,281	$19.58	-	-	$282.82	$302.40
Onshore Wind	3,039	5,669	21.3%	1.3%	$2,701	$14.78	-	-	$260.44	$275.22
Offshore Wind	9,000	29,665	37.6%	6.8%	$8,588	$34.94	$0.01	-	$219.61	$254.56
Biomass	258	2,261	100.1%	0.5%	-	$15.02	$5.06	-	-	$20.08
Sub Total	39,137	169,017	49.3%	72.4%		$19.30	$1.42	$2.07	$116.19	$138.98

Dispatchable	**Capacity** MW	**Generation** GWh/yr	**Capacity Factor** %	**% Total Load**	**Capital Cost** $/kW	**Fixed O&M** $/MWh	**Variable O&M** $/MWh	**Fuel Cost** $/MWh	**Capital Recovery** $/MWh	**Native Generation Cost** $/MWh
DEFR	24,000	34,656	16.5%	7.9%	$5,988	$79.27	$3.14	$4.61	$212.05	$299.06
Sub Total	24,000	34,656	16.5%	14.8%	-	$79.27	$3.14	$4.61	$212.05	$299.06
Native Generation		203,673								$166.22

Regional purchases	Purchased GWh/yr	% Total Load		Total GWh	% Total Load
NE and PJM Purchases	8,665	3.7%	Curtailments	10,665	2.4%
Canada Purchases	21,080	9.0%	Unmet Load	0	0.0%
Sub Total	29,745	12.7%			
Total	233,418	100.0%			

Table B-3-2: Brighter Future 1 Generation and Costs (2040)
at $5,988/kW DEFR capital cost

Generation Summary				Brighter Future 2 (2040)						
Non-dispatchable	Capacity MW	Generation GWh/yr	Capacity Factor %	% Total Load	Capital Cost $/kW	Fixed O&M $/MWh	Variable O&M $/MWh	Fuel Cost $/MWh	Capital Recovery $/MWh	Native Generation Cost $/MWh
Existing Nuclear	3,305	26,700	92.2%	11.5%	$141	$28.61	$1.22	$4.09	$2.84	$36.75
New Nuclear	7,000	58,579	95.5%	13.5%	$9,992	$15.22	$2.48	$4.10	$61.06	$82.85
Hydro	5,485	34,037	70.8%	7.9%		$7.06	$1.48			$8.54
PV BTM	9,000	10,436	13.2%	2.4%	$4,647	$17.25	-	-	$720.81	$738.06
PV Grid	2,050	2,041	11.4%	0.5%	$1,281	$16.02	-	-	$231.38	$247.39
Onshore Wind	3,039	6,438	24.2%	1.5%	$2,701	$13.01	-	-	$229.32	$242.34
Biomass	258	2,261	100.1%	0.5%	-	$15.02	$5.06	-	-	$20.08
Sub Total	30,137	140,493	53.2%	60.2%		$15.84	$1.71	$2.49	$93.41	$113.44

Dispatchable	Capacity MW	Generation GWh/yr	Capacity Factor %	% Total Load	Capital Cost $/kW	Fixed O&M $/MWh	Variable O&M $/MWh	Fuel Cost $/MWh	Capital Recovery $/MWh	Native Generation Cost $/MWh
DEFR	27,000	59,259	25.1%	25.4%	$5,988	$104.30	$3.14	$4.61	$139.51	$251.57
Sub Total	27,000	59,259	25.1%	25.4%		$104.30	$3.14	$4.61	$139.51	$251.57
Native Generation		199,752								$154.42

Regional purchases	Purchased GWh/yr	% Total Load		Total GWh	% Total Load
NE and PJM Purchases	12,572	5.4%	Curtailments	969	0.4%
Canada Purchases	21,080	9.0%	Unmet Load	0	0.0%
Sub Total	33,652	14.4%			
Total	233,404	100.0%			

Appendix C: Energy Source Assumptions

	Existing Nuclear	New Nuclear	DEFR (Flex Nuclear)	Storage	PV BTM	PV Grid	Onshore Wind	Offshore Wind
Overnight Capital Cost ($/kW)	116	8,632	5,173	1,387	4,600	1,205	2,491	8,386
Interest During Construction ($/kW)	26	1,361	815	0	47	76	211	202
Total Capital Cost ($/kW)	141	9,992	5,998	1,387	4,647	1,281	2,701	8,588
Depreciation schedule	22 years	21 years	24 years	15 years	20 years	20 years	20 years	20 years
Fixed O&M ($/kW-year)	231	127	114	26	20	16	28	115
Variable O&M ($/MWh)	1.22	2.48	3.14	0.00	0.00	0.00	0.00	0.01
Fuel Cost ($/MWh)	4.09	4.10	4.61	-	-	-	-	-
Nameplate Capacity (MW)	1,245	2,156	500	50	0.01	150	200	400
Capacity Degradation over Lifetime	2%	2%	2%	10%	5%	10%	10%	10%
Charging Rate (% of Max Output MW)	0	0	0.69	1.00	0	0	0	0
Storage Capacity (hours)	0	0	5.5	4.0	0	0	0	0