Energy Resilience and Efficiency in Maryland

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Preface

The Maryland Climate Solutions Now Act of 2022 (SB0528, henceforth "The CSNA") sets a target for reducing greenhouse gas (GHG) emissions from the Maryland economy by 60% by 2031 (relative to the estimated 2006 emissions) and to achieve a net-zero goal by 2045. The CSNA established several Working Groups, including the Energy Resilience and Efficiency Working Group (EREWG), and charged with advising the Maryland Climate Change Commission (MCCC) on topics specified by the CSNA and conducting studies.

In support of the EREWG, the Johns Hopkins University (JHU) has been contracted to undertake a study addressing the role of energy storage research and technologies in improving electric power grid resiliency and supporting electric power decarbonization. Supporting distributed renewable energy projects and energy storage systems can enhance grid resilience, ensuring critical facilities remain operational during widespread power outages, including the threats imposed by natural disasters, extreme weather events (e.g., hurricanes, heatwaves, wildfires) and potential attacks of both cyber and physical nature. Specifically, this study falls within Section 2–1303.3 of the CSNA that specifies that the EREWG will conduct a study on topics concerning the development and deployment of electricity storage and renewable energy technology, electric grid distribution, re-use of previously developed energy production sites, and the lifespan and viability of energy facilities that do not emit GHGs.

The present report was supported by funding provided by the Maryland Department of the Environment (MDE) and administered by the University of Maryland. The work reported was undertaken by faculty and students affiliated with the JHU Ralph O'Connor Sustainable Energy Institute (ROSEI). The EREWG and its members were regularly consulted by the JHU researchers while conducting these analyses to inform the Working Group of the study's progress and to review its assumptions. The authors are grateful for the suggestions and information provided by EREWG members. However, Johns Hopkins University is solely responsible for the analyses and their conclusions in this document, and for any remaining errors and opinions expressed.

The specific topics mandated by the CSNA are listed below, along with the specific sections of this report that address them:

(I) Methods for the state to encourage electricity storage technology research (Section 1);
(II) Methods of increasing the security of the electricity grid by supporting distributed renewable energy projects and energy storage with the potential to supply electric energy to critical facilities during a widespread power outage (Section 2);
(III) Potential electric grid distribution transformation projects (Section 3);
(IV) The potential to develop clean energy resources on previously developed project sites (Section 4); and
(V) The lifespan and viability of energy facilities in the state that do not emit greenhouse gas (Section 5), including:
    1. Solar energy generating facilities;
    2. Nuclear energy generating facilities;
    3. Wind energy generating facilities;
    4. Geothermal energy generating facilities;
    5. Hydroelectric energy generating facilities; and
    6. Biofuel energy generating facilities

Executive Summary

This report, prepared by the Ralph O'Connor Sustainable Energy Institute (ROSEI) at Johns Hopkins University (JHU), responds to the mandate outlined in Section 2–1303.3 of the Maryland Climate Solutions Now Act (CSNA) of 2022. The CSNA sets ambitious goals for Maryland, including reducing greenhouse gas emissions by 60% by 2031 relative to 2006 levels and achieving net-zero emissions by 2045. In support of the Energy Resilience and Efficiency Working Group (EREWG), this study addresses key topics related to electricity storage and renewable energy technologies, electric grid modernization, the redevelopment of energy production sites, and the viability of non-emitting energy facilities.

The report first qualitatively explores methods for encouraging the research and deployment of electricity storage technologies, which are critical to maintaining grid reliability and supporting renewable energy integration. Policies such as state procurement targets, financial incentives, and federal frameworks have been instrumental in driving storage growth nationwide. This section also emphasizes the role of capacity expansion planning in maximizing the benefits of storage deployment, with a focus on balancing grid operations, consumer needs, and the evolving demands of a clean energy transition.

Next, the report examines how distributed renewable energy systems and storage can enhance the resilience of Maryland's electricity grid given the power outage profile in Maryland over the past several years. As extreme weather events and other disruptions increasingly threaten grid reliability, this analysis identifies critical infrastructure needs and outlines strategies to ensure uninterrupted service for vulnerable populations and essential facilities. It demonstrates the importance of deploying storage, in combination with other distributed energy resources, to mitigate the effect of long outages on vulnerable consumers and critical loads.

Transforming distribution systems to accommodate renewable energy and growing electricity demand is essential for ensuring reliable power supply while achieving the state's clean energy goals. This section highlights opportunities for integrating technologies such as energy storage to reduce grid congestion, support offshore wind development, and enhance system reliability. Policies like FERC Orders No. 2222 and No. 1920 provide a framework for advancing these objectives while addressing challenges related to bidirectional energy flows and distributed energy resource integration. Repurposing previously developed energy sites for renewable projects represents a significant opportunity to leverage existing infrastructure while expanding Maryland's clean energy capacity. The report assesses the potential for solar, wind, and bioenergy projects at retired and operational fossil-fueled power plant sites, identifying solar energy as the most viable option across multiple locations. The analysis also considers site-specific and system-wide planning to ensure efficient and sustainable redevelopment.

Finally, the report describes the lifespan and viability of non-emitting energy facilities in Maryland, including solar, wind, nuclear, geothermal, hydroelectric, and biomass technologies. As many existing facilities near the end of their operational lives, proactive investment in renewable energy and storage systems will be essential to maintaining and expanding the state's clean energy infrastructure. This section provides recommendations for extending the operational viability of key facilities and prioritizing resources for future development.

1. Methods to Encourage Electricity Storage Research and Deployment

In this section, we discuss the *"(m)ethods for the state to encourage electricity storage technology research*". Section 1.1 reviews the state and federal policies designed to encourage electricity storage investment and research. In Section 1.2, we examine how capacity expansion planning can be used to estimate the value of storage deployment to the power system and consumers.

1.1. Policies to Encourage Storage Investment

California and Texas lead the nation in storage deployment, representing 55% and 24% of the country's 13.2 GW of storage capacity in 2023, respectively [1]. In 2013, California developed an energy storage procurement target of 1.3 GW by 2020 under the advisement of the California Public Utilities Commission (CPUC[1] [2]. Between 2013 and 2024, the California legislature passed multiple bills to study and develop location- and technology-specific storage programs, resulting in an estimated 14 GW of grid-scale storage by December 2024 [3], [4], [5]. California also provides incentives of \$250-\$300/kWh for storage for all-electric home developments (with a \$5 million budget) [6].

In contrast, Texas's energy storage growth was not initiated by mandates, but rather through a combination of the market incentives pressure, fast permitting, and high capacities of variable renewable resources. In Texas, high penetrations of renewables and limited inter-regional transmission makes storage profitable as a provider of energy arbitrage ("charge at cheap prices and discharge at high prices") or reliability services [7]. Other states have also developed plans to increase deployment. In the context of energy storage capacity and target year goals, New York's 2019 Climate Leadership and Community Protection Act is perhaps the most relevant, with a codified procurement target of 3 GW by 2030 [8]. In 2024, the New York Department of Public Service expanded this goal to 6 GW of storage in 2030, of which 200 MW would be for new residential-scale solar and 1.5 GW for new commercial and community-scale solar [9]. The funding for that program is anticipated to be at least \$2 billion [10].

Maryland has developed regulatory requirements, demonstration programs, and financial incentives to support storage investment. Under House Bill 910 in 2023, Maryland passed an energy storage procurement target to promote "energy storage device" investments [11]. Importantly, the Bill defines energy storage devices rather broadly, allowing for various physical and virtual mechanisms for energy storage, e.g., thermal storage, electrochemical storage, virtual power plants, and hydrogen-based storage. The Bill requires *at least* 0.75, 1.5, and 3 GW of cumulative energy storage capacity by the years 2027, 2030, and 2033, respectively. To advance cost-effective storage deployment, the bill establishes the Maryland Energy Storage Program, which will design and manage market-based incentives and energy storage credits by 2025.

Recent federal activity also aims to boost energy storage adoption. The 2022 Inflation Reduction Act (IRA) expanded existing federal tax credits for storage co-located with solar to include a 30% investment tax credits for stand-alone storage [12]. Energy storage received a further push through the 2021 Infrastructure Investment and Jobs Act (IIJA) [13]. The Infrastructure Bill seeks to boost domestic energy storage production by providing \$6 billion in supply chain investments and \$3 billion for manufacturing support. The Infrastructure Bill also provides funding for state- and utility-run resiliency programs and demonstration projects. Importantly, both the IRA and IIJA are both complementary to available state incentives.

In addition to procurement programs (as in California and Maryland) and tax subsidies (as in the IRA), support of basic and applied research at both the state and federal level have played

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[1] A public utilities commission provides oversight and regulation for public utilities such as energy and water. In the U.S., each state has a public utility commission.

a crucial role in expanding technological options for storage and lowering its cost. The largest such state-level program by far is sponsored by the California Energy Commission, which has earmarked $270 million to demonstrate and deploy non-lithium iron technologies for long duration energy storage in the state [14]. More recently, in October 2024, NYSERDA announced 26 projects, totaling $24 million, to support research, development and deployment of advanced long-duration storage, clean hydrogen, grid modernization and building efficiency technologies [15]. Other states, including Maryland, have also established research programs, often at or with flagship universities, to address fundamental engineering science and practical applications of both established lithium-ion technologies and emerging long-duration technologies. For instance, the University of Maryland's Maryland Energy Innovation Institute (MEI^2) is dedicated to the development of clean energy technology (primarily energy storage) to address climate change, stimulate economic growth, and create a sustainable future. The center has spun off a number of battery technology companies including Ion Storage Systems, Aqualith, WH-Power, and Ionic Devices. Other Maryland-based research institutions, such as JHU's ROSEI, have undertaken research on fundamental materials science and chemistry underlying emerging storage technologies, as well as on mathematical and economic methods to integrate storage into renewable energy systems. An example elsewhere is the Pennsylvania State University Battery & Energy Storage Technology (BEST) Center [16]. This center prioritizes research on advanced materials (anode, cathode, separator, and electrolyte), cell development and system-level innovations, including reduced-order modeling, SOC and SOH estimation, smart battery management systems, and hybrid vehicle integration.

1.2. Value of Storage for Energy Transition

Storage technology is indispensable in the clean energy transition. However, the value of storage integration for the clean energy transition depends on its ability to enhance grid reliability, provide cost-effective energy arbitrage, support resource adequacy, and address spatio-temporal mismatches between renewable energy generation and demand, and reduce curtailment of renewable energy generation. Capturing this value requires strategic deployment, supportive policies, and advancements in storage technology to align with the needs of an increasingly variable and distributed power grid. From the technical viewpoint, this raises two challenges: understanding operational capabilities of energy storage (e.g., new cost/benefit tradeoffs created by the energy limited nature of these resources and potential degradation of energy careers) and integration of these capabilities with tools used for techno-economic power grid analysis and expansion planning (e.g., multi-period time coupling).

Specifically, capacity expansion planning is particularly important for storage deployment as it aims to account for the complex technical and economic attributes of the power system to identify a collection of investment decisions, across all potential generation and transmission resources (including storage), that reduce costs or achieve policy goals. However, accurately capturing the value of batteries under high penetrations of variable renewable generation necessitates higher temporal resolution and is still, to a large extent, an open modeling question. The expertise at Ralph O'Connor Sustainable Energy Institute (ROSEI), which complements the expertise of MEI^2 in developing energy storage devices, addresses this practice gap by developing modeling tools for capturing the value of energy storage for power grid operations.

In particular, a large portion of the value of storage to the grid is derived from the temporal shifting of energy - storing excess electricity production for hours with lower electricity generation, higher marginal emissions, or peak electricity demand. Approximately three-quarters of US battery storage is used primarily for such energy shifting [17]. The temporal coupling of resources must be included to identify high-value locations from storage. As temporal coupling drives the value of storage, opportunity cost underlies operational (dis)charging decisions, rather than fuel costs. In addition, storage degradation costs impact operational decisions and are particularly acute for lithium-ion batteries. Intensive use of batteries accelerates battery aging from chemical and physical stressors. Significantly, operational decisions that minimize degradation costs may yield lower profit. The tradeoff between opportunity cost and degradation cost underpins storage operations and the identification of profitable deployments. Due to the unique attribute of storage, a shift in planning and market valuations is necessary to optimize storage technologies.

To ensure the societally optimal use of public and private resources in achieving storage deployment targets, it is essential to guide storage deployment processes with value-driven decisions in addition to regulatory requirements, demonstration programs, financial incentives, and other strategic measures.

2. Enhancing Grid Security Through Distributed Renewables and Energy Storage to Power Critical Facilities During Outages

The security of the electricity grid is paramount, especially in the face of increasing threats from natural disasters and potential attacks of both cyber and physical nature. Supporting distributed renewable energy projects and energy storage systems can enhance grid resilience, ensuring critical facilities remain operational during widespread power outages. However, the usefulness of these resources in enhancing power grid resilience depends on their strategic placement, reliable integration with existing infrastructure, coordination with grid management systems, and the development of policies and technologies that enable rapid response and recovery during emergencies. Importantly, the usefulness also depends on the ability to match storage availability with the causes, locations and durations of outages. This section explores the causes of outages, identifies vulnerabilities, and discusses qualitative strategies to enhance grid security through renewable energy and storage solutions.

Section 2 addresses the CSNA's mandate to study "*(m)ethods of increasing the security of the electricity grid by supporting distributed renewable energy projects and energy storage with the potential to supply electric energy to critical facilities during a widespread power outage."* In particular, we review causes of outages in Maryland (Section 2.1), a working definition of critical loads (Section 2.2), and methods for enhancing the resilience of critical loads (Section 2.3).

2.1. Causes of Outages and Vulnerabilities

Outages are caused by various factors, including extreme weather events, operational problems, and both physical and cyber attacks on the network. According to the Energy Information Administration's (EIA's) Electric Emergency Incident and Disturbance Report, which collects information about primarily large-scale and transmission-level outages, extreme weather events have caused the majority of annual outages in Maryland as shown in Figure 1 [18]. Table 1 reports example data from two years: one year with large outages (2012) and one year without (2023). From 2003 to 2023, Maryland experienced sixty-one weather related outages due to thunderstorms/lighting (20 events), winter weather (9), and hurricanes (7). Hurricanes Isabel, Wilma, Irene and the 2012 North American Derecho caused the longest outages with an average restoration time of approximately 7 days. During the same period, operational problems from equipment failures (3) and "complete loss of monitoring" (10) led to outages on average 2.4 hours long. Physical and cyber attacks are increasingly contributing to outages in Maryland. Of the thirty-four reported attack-induced outages, physical attacks such as vandalism were the cause for thirty outages. Outages due to physical and cyber attacks are restored quickly on average, but of course have the potential for more severe consequences.

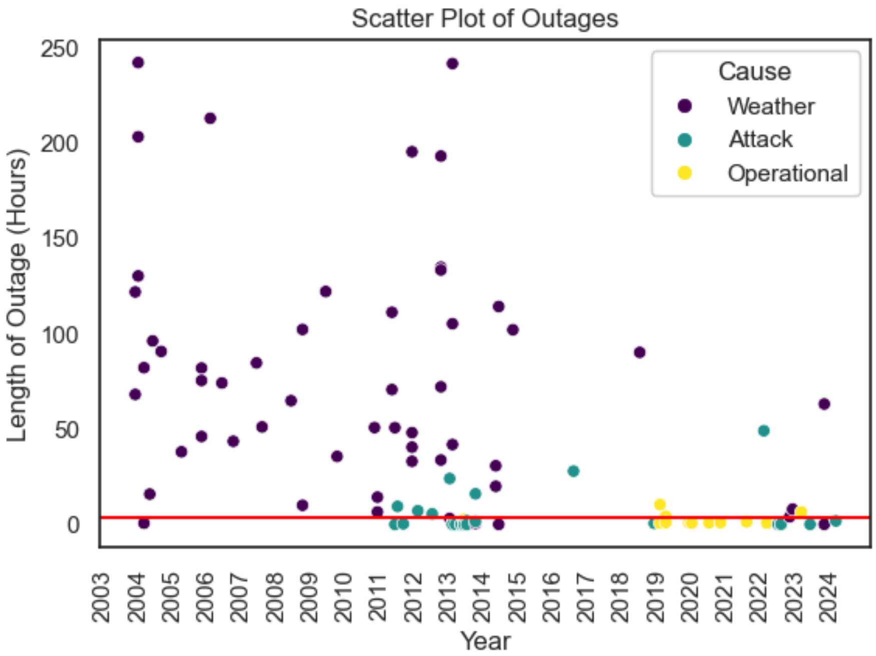

Figure 1: Outages in Maryland plotted by outage starting date and length of outage where each point indicates an individual outage report. Scatter plot color indicates the primary cause for the outage as reported by the utility company [18]. The red horizontal line marks 4 hours, a typical duration of commercially available battery storage units.

Table 1: Example of annual data on outages in Maryland organized by primary cause as reported by EIA [18]. Note that many outages are missing loss, customers affected, or length of outage; averages are over outages that report numbers.

Cause	Mean Length of Outage (Hours)	Mean Customers Affected	Mean Loss (MW)	Number Outages
Weather or natural disaster (2012)	130	152,500	490	7
Physical Attack, Vandalism (2012)	3	0	0	11
Weather or natural disaster (2023)	32	42,800	Unknown	5
Suspicious Activity (20223)	0.03	0	0	1

Complementary to the high-level EIA indicators summarized above, distribution system reliability is often measured using two indices - the “system average interruption duration index” (SAIDI) and “system average interruption frequency index” (SAIFI) [19]. The SAIDI measures the total duration of power interruption an average customer experiences in a year. In 2023, SAIDI among Maryland utility companies ranged from 1.0 to 3.4 hours, well below the U.S. average SAIDI of 5.6 hours. Maryland customers also experienced few outages per year, as measured by the SAIFI index of outages per customer per year. The U.S. average SAIFI is 1.4 outages per customer in that year, while SAIFI among Maryland utility companies ranges between 0.4 and 1.3. In 2023, Maryland did not experience widespread extreme weather, contributing to a lower SAIDI and SAIFI. However, after controlling for major events, electricity customers in Maryland still experience fewer outages and shorter duration outages than the average U.S. customer.

In Table 2, the effect of major events on network reliability is compared for the years 2022 and 2023. Although severe outages are a minority of events (roughly a quarter of events in each year), they account for most of the hours of outages (approximately two-thirds). On average, outage events last less than the typical storage of lithium-ion electricity storage batteries for grid use (about 4 hours), but severe events on average last much longer (roughly 8 hours). This implies that if lithium-ion batteries are to be used as power back up, they either need to be oversized relative to the load to be met since a typical 4 hour storage would not be enough for severe outages, or the load to be supplied by batteries needs to be rationed to the most important power requirements. As discussed in Section 2.3, resiliency of critical loads to power outages can be enhanced if energy storage is coupled with other technologies (e.g., distributed energy resources and microgrid solutions).

Table 2: Summary of reliability indices for the State of Maryland (from https://www.eia.gov/electricity/annual/html/epa_11_02.html). The types of events considered are severe events and non-severe events. Note: Computations excluding severe events, such as extreme weather, (second row in each year) provide information on more typical day-to-day performance of the power system. When including severe events (third row in each year) together with minor events in annual totals (first row in each year), all indices increase.

	Types of Events Considered	**SAIDI**	**SAIFI**	**CAIDI**
		Hours per Year	*Outages per Customer per Year*	*Outage Duration Experienced by a Customer (Hours/Event)*
2022	All events	4.3	1.16	3.7
	All, excluding severe events	1.4	0.84	1.6
	Only severe events	2.9	0.32	9.2
2023	All events	2.8	0.9	3.0
	All, excluding severe events	1.1	0.7	1.6
	Only severe events	1.7	0.2	7.7

Maryland utility companies' SAIDI (System Average Interruption Duration Index) ranged from 1.0 to 3.4 hours, aligning closely with the discharge duration of commercially available battery units, which typically sustain a constant power output for 4-6 hours (Table 2). This indicates the technical feasibility of using strategically deployed battery storage to enhance the resilience of critical loads during average outages. Moreover, multi-stacked battery systems can extend discharge duration for prolonged outages through sequential operation. Additionally, mobile storage solutions, often referred to as "batteries on wheels," can provide power to critical loads and then be relocated for recharging, further increasing the duration of discharge they can provide to critical loads. Finally, long(er)-duration storage technologies (with durations above 4-6 hours), some of which are under development at MEI[2], can provide better support for dealing with extremely long outages. As discussed below, tighter resiliency assurances can be attained if storage capabilities are reinsured with additional and, possibly, co-located resources.

2.2. Critical Loads

Although Maryland customers generally experience infrequent, short-duration outages, critical infrastructure (CI) and vulnerable customers require guaranteed and continuous service. CI, or critical facilities, provide essential services to society. CI includes hospitals, fire and police stations, banks, prisons, public utilities (e.g., water, electricity, and sewage), and transportation systems [20], [21]. In addition, vulnerable customers, including the elderly, bear a higher health and safety risk during outages and may rely on electricity for vital medical devices. Such critical infrastructure and vulnerable customers require uninterruptible power sources.

As discussed in Section 2.1, power outages can last much longer than the 4 hour capacity typical of lithium-ion batteries. During such outages, relying solely on battery storage requires either prioritization and/or rationing of critical loads or adding extra battery capacity. The cost of adding 10+ hours of storage is likely to decrease over the next two decades, but is currently high. For such critical loads as hospitals or water/wastewater treatment plants, long-duration back-up power is needed for outages lasting days (e.g., the 2012 Derecho). Combining battery storage with internal combustion and/or clean energy distributed energy resources (e.g., solar panels) can further enhance resiliency. Although clean energy distributed energy resources (DERs) will not completely obviate the need for internal combustion resources for long-duration outages, they may reduce their impact on air quality. Unlike weather-dependent DERs, internal combustion resources provide continuous power output and allow for long-term fuel storage.

In the following section, we will discuss resilient energy solutions to increase grid reliability and guarantee service for *vulnerable groups at critical loads*; however, additional analysis is required for resilient energy solutions targeted for vulnerable groups among the general population, which is beyond the scope of this report.

2.3. Enhancing Resilience of Critical Loads

Enhancing the resilience of critical loads to power outages involves implementing a variety of technologies with a wide range of costs. Traditionally, on-site back-up generators (typically, diesel) have been used to supply electricity during outages, but they contribute to local air pollution.[2] Additional fuel types for back-up generators may include natural gas, propane, and fuel cells. However, extreme weather events can disrupt supply chains, and infrequent use often leads to inadequate maintenance, increasing the likelihood of generator failure [23]. In contrast, energy

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[2] Air pollution regulators have become increasingly concerned about use of behind-the-meter generation from diesels to meet demands during outages or high electricity demand days [22].

storage technologies offer both emergency backup power and continuous use during normal operations for grid services, such as load shifting and black-start capabilities [24]. Storage systems can be deployed either on the utility side (front-of-the-meter, or FTM) or the customer side (behind-the-meter, or BTM, and off-grid). When coordinated by utilities, community energy storage (CES) systems that combine BTM and FTM storage can deliver community-wide resilience. However, the effectiveness of storage during prolonged outages is constrained by its capacity and state of charge at the onset of the interruption.

To address long-duration outages, storage can be co-located with other DERs, such as solar photovoltaic (PV) systems and combined heat and power (CHP) plants. Local grids with sufficient generation, storage, and control capabilities can function as stand-alone microgrids. Still, microgrids in the U.S. are expensive, with costs ranging from \$2 to \$4 million per MW due to the high expense of generation and advanced control systems [23].

Table 3: Comparison of the benefits and limitations of resilient energy solutions.

Technology	Benefits	Limitations
Storage	Simple, scalable implementation; Provides additional value streams	Limited duration (4-6 hours)
Community Energy Storage	Centralized support; Enhances community resilience	Requires coordination, potential uneven benefits
Storage + DER	Extended backup duration; Renewable integration	Higher costs, complex integration
Back-up Generators	Relatively inexpensive and reliable	Difficulty in resupplying fuel during extended outages

Resilient energy solution selection must depend on load type, desired levels of reliability, and location. For critical infrastructure and vulnerable customers, only storage plus DERs and back-up generators can act as an uninterruptible power source for long duration outages. However, guaranteed service comes at a high cost, likely beyond the value ascribed by most end-use consumers, exceptions being facilities critical for health and safety, such as hospitals and water treatment and supply facilities [20], [21].[3] As indicated by the SAIDI values of utility companies in Maryland (see above), the majority of outages are less than 4 hours and suitable for battery storage. However, a significant fraction of outages can be 4 hours or longer (see Fig. 1), and critical loads would likely still need to install back-up generation capacity, at least until the cost of very long-duration battery storage (e.g., more than 24 hours) decreases significantly.

Improving building performance through efficiency measures and envelope improvements improves resilience by reducing (but not eliminating) the need for storage or back-up generation capacity. Improved energy efficiency has the additional benefit of reducing customer energy burden[4] throughout the year [25], whereas internal combustion generation is typically subject to restrictive regulation and would be used rarely. BTM and clean energy DERs, in contrast, have the potential to be profitably used to arbitrage between high and low-price hours and to provide other grid services, under suitable retail rate structures.

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[3] The value of lost load (VOLL), customer damage functions (CDFs), and cost-benefit analyses are common methods for estimating the value of potential resilience enhancements.

[4] Energy burden measures the portion of income that customers spend on energy bills.

Increasing the security of the electricity grid through distributed renewable energy projects and energy storage is attractive for maintaining most critical services during the most frequent types of outages. Back-up diesel generators would only be necessary when risks of extended outages could endanger health and safety. As battery costs decline, their share of the market for back-up power will expand at the expense of fossil fuel. In understanding the existing vulnerabilities to Maryland’s grid, we can identify optimal pathways to secure a resilient power system for all customers, balancing economic, reliability, and environmental considerations.

3. Potential Electric Grid Distribution Transformation Projects

Maryland aims to reduce greenhouse gas emissions by 60% by 2031 and achieve net-zero emissions by 2045 [26]. Transforming the electric grid's distribution systems is critical to accommodate 1) increasing in-state renewable energy capacity, both as a FRM and BTM resources, 2) clean energy imports, and 3) rising electricity demand driven by electrification initiatives. Maryland’s ambitious plans include the integration of 8.5 gigawatts of offshore wind energy as envisioned in the POWER Act [27], alongside growing electricity needs from electric vehicles, building decarbonization programs such as the EmPOWER [28] initiative, enacted Building Energy Performance Standards [29] and potential Zero-Emission Heating Equipment Standard [30], which is currently under consideration, agricultural electrification [31], and other industrial advancements. Energy storage emerges as a pivotal technology in these transitions.

Against this backdrop, the CSNA mandates a study of “*(p)otential electric grid distribution transformation projects.”* Modernizing distribution systems presents both technical challenges and opportunities to align Maryland’s energy landscape with decarbonization and grid resilience objectives. Distribution systems must integrate renewable projects, support electrification-driven load growth, and align seamlessly with transmission modernization, as these efforts are inherently interconnected. Energy storage serves as a cornerstone of this transformation, offering services such as reducing energy losses, increasing hosting capacity for distributed energy resources (DERs), deferring costly infrastructure upgrades, and maintaining voltage and frequency stability. This section examines transformative potential for distribution modernization and its implications for decarbonization scenarios within the HOPE-MD framework.

This section reviews trends in distribution modernization (Section 3.1), potential future roles for storage and modernization (Sections 3.2, 3.3), how modernization can help manage load growth (Section 3.4), and factors affecting the pace and direction of the energy transition (Section 3.5).

3.1. Modernizing Distribution Systems: Evolution and Drivers

Historically, distribution networks were unidirectional, delivering electricity from centralized power plants to end-users, optimized for predictable demand and fossil fuel-based generation. However, the growing penetration of renewable energy sources such as solar PV and wind power, combined with rising electrification, necessitates a shift toward flexible, adaptive networks capable of supporting bidirectional energy flows and advanced grid services. However, these bidirectional flows introduce technical challenges such as voltage fluctuations, protection coordination difficulties, and inefficiencies in power flow management [32], underscoring the need for modernized grids capable of handling the dynamic interplay between transmission and distribution systems [33]. Policies and regulations are stepping in to address these complexities, creating pathways for better integration of DERs and energy storage systems.

Regulatory advancements like FERC Order No. 2222 [34] and No. 1920 [35] are pivotal to this transformation. Order No. 2222 requires rules to be created for DERs, including storage, to participate in wholesale (transmission) electricity markets individually or in aggregations, enabling DERs to provide energy, capacity, and ancillary services such as voltage stabilization. However, implementing these changes requires complex coordination between transmission and distribution systems, especially for aggregated DERs spanning multiple distribution networks. Order No. 1920 emphasizes scenario-based regional transmission planning to integrate renewable energy and enhance grid reliability and the adoption of advanced technologies such as real-time monitoring and control algorithms to manage the operational complexities of bidirectional flows. Together, these policies drive a more flexible and efficient grid, enhancing DER integration and system performance. Demonstrations such as California's Demand Response Auction Mechanism (DRAM), which aggregates at least 22 MW of DERs for wholesale market participation to reduce transmission congestion and improve reliability during peak demand [36], and Massachusetts' virtual power plant (VPP) program, where utilities such as National Grid and Eversource compensate customers for allowing control of home batteries [37], further highlight the potential of coordinated DER integration to enhance reliability and flexibility.

Building on the experience of other states, Maryland is positioned to leverage distribution system modernization to advance its clean energy goals. The planned integration of 8.5 GW of offshore wind capacity and the growing electrification of transportation and buildings will add additional requirements and constraints on the use of both transmission and distribution networks. Strategically deploying energy storage systems could alleviate grid congestion in high-demand areas, improve the resilience of critical infrastructure, and support the integration of large-scale renewable projects like offshore wind. These investments are essential for meeting the state's climate goals, ensuring that Maryland's grid is prepared to deliver reliable and affordable sustainable energy for decades to come.

3.2. Energy Storage as a Critical Component for Distribution Modernization

Energy storage systems are central to modernizing distribution networks, offering enhanced flexibility, grid resiliency, and optimized infrastructure utilization [38]. By storing energy during low demand periods and releasing it during peaks, storage systems balance supply and demand, a key function for managing the intermittency [39], [40]. Energy storage mitigates fluctuations in generation by capturing surplus energy during periods of high production—such as midday for solar or windy nights offshore—and making it available during times of lower generation or higher demand, ensuring a stable and reliable power supply and minimizing curtailment while maximizing clean energy resources utilization [41].

Insights from New York's Reforming the Energy Vision [42] initiative and California's grid modernization efforts [43] illustrate the transformative potential of energy storage. Insights from New York's Reforming the Energy Vision [42] initiative and California's grid modernization efforts [43] illustrate the transformative potential of energy storage. These programs highlight the importance of creating platforms for real-time coordination between DERs and storage at the distribution level. Hosting capacity analysis, a critical tool in both initiatives, helps identify optimal locations for storage deployment, reducing integration costs and enhancing grid performance. Maryland can adapt these practices to integrate renewable energy more efficiently, manage peak demand, and enhance grid resiliency, particularly in the context of expanding offshore wind capacity and growing electricity demand from electrification.

3.3. Potential of Distribution Modernization to Enhance Power Grid Resiliency

The innovations described above also enhance resiliency posed by extreme weather events such as hurricanes, wildfires, and heatwaves. Resiliency measures include hardening infrastructure, such as upgrading power lines and substations or converting overhead lines to underground systems, which significantly reduce the vulnerability of critical assets.

For example, Florida’s $1.7 billion undergrounding program by Duke Energy has shown reduced outages on underground lines compared to overhead systems during hurricanes like Irma [44]. These efforts aim to complete the conversion of 1,300 miles of lines by 2032, reducing outage durations and restoration costs. For example, Florida’s $1.7 billion undergrounding program by Duke Energy has shown reduced outages on underground lines compared to overhead systems during hurricanes like Irma [44]. These efforts aim to complete the conversion of 1,300 miles of lines by 2032, reducing outage durations and restoration costs.

Additionally, DERs like rooftop solar panels and batteries, provide localized generation and storage that can significantly increase the likelihood that essential facilities remain operational during grid disruptions. In California’s September 2022 heatwave, battery storage supplied 3.4 GW of peak generation, preventing outages despite demand reaching 51.4 GW, surpassing the 46.8 GW peak that caused blackouts in 2020 [45]. Similarly, during Hurricane Ida, DERs in Louisiana maintained power for critical infrastructure even as the central grid failed [46]. Microgrids further enhance resilience by enabling isolated operation for hospitals and emergency shelters, reducing dependence on centralized systems during disasters [47]. As pointed out in Section 2, the present cost of long-duration storage and the risk of long, even multi-day power outages, are likely to imply that for critical loads it will be necessary to retain some internal combustion back-up capacity. However, the lithium-ion battery storage and clean energy DERs (e.g., solar panels) would allow for operating internal combustion less often.

In 2012, the State of Maryland explored undergrounding and microgrids as methods to increase resilience of residential power deliverability in the face of multi-day outages caused by hurricanes and derechos, although the expense of such measures at that time was ultimately concluded to be greater than the benefits [48]. However, as the cost of distributed energy generation and storage have decreased greatly since that time, revisiting these measures and focusing their deployment on critical loads may result in more favorable conclusions about their deployment.

3.4. Potential of Distribution Modernization to Support Load Growth

The electrification of transportation, industry, and buildings is critical to the clean energy transition. As these sectors transition from fossil fuels to electricity, distribution networks face unprecedented increases in demand. For instance, electric vehicles (EVs) are projected to account for 14.2%-15.6% of total US electricity consumption by 2035, significantly reshaping energy demand patterns [49]. While EV charging adds challenges to grid management, it also presents opportunities through vehicle-to-grid (V2G) technology, where EVs act as mobile energy storage units on the demand side [50]. For example, in December 2020, five Lion Electric battery-electric buses in White Plains, NY, supplied power to Con Edison customers, showcasing V2G's potential to enhance grid flexibility. However, fully realizing these benefits requires transforming distribution networks to manage the increased demand and integrate bidirectional energy flows effectively [50].

3.5. Summary of Factors Influencing Clean Energy Transition Scenarios

Scenario development for the clean energy transition is guided by critical drivers that address Maryland's potential to transform electric power distribution systems:

1. **Electrification- and technology-driven driven Load Growth**: Increased electricity demand from EVs, electrified heating, data centers, and industrial decarbonization necessitates precise grid planning. In addition to decarbonization, significant load growth is expected due to the deployment of new energy-intensive technologies, which are critical for economic development (e.g., data centers, hydrogen electrolyzers and possibly clean manufacturing). Scenarios must evaluate the timing and location of demand growth to prevent overloading distribution networks.
2. **Renewable Energy Integration**: The planned addition of 8.5 GW of offshore wind, even if not fully executed or executed with delays, introduces challenges related to intermittent production and transmission-distribution interconnection. Scenarios should incorporate geographic diversity and operational strategies for managing variability using a holistic set of existing and emerging technologies, e.g., inter-regional transfer capability, demand-side management, energy storage, and coordination with other low-emissions generation resources.
3. **Energy Storage Deployment**: Strategic deployment of storage systems is crucial for addressing renewable variability and peak load demands. Scenarios should optimize storage placement to enhance reliability and defer costly infrastructure upgrades.
4. **Regulatory and Policy Frameworks**: State-level policies like the CSNA and other enacted (e.g., Renewable Portfolio Standard) or planned initiatives set the pace for emissions reductions and clean energy adoption. Scenarios must reflect the impact of these policies on infrastructure, costs, and technology adoption rates.

4. Potential for Repowering Developed Plant Sites with Renewables

Fossil-fueled power plants currently account for three-quarters of the state's generation capacity and 46% of its generation (see Table 4), some of which may near the end of their technological or economic lifetime before 2035. A viable solution to leverage existing interconnection is via repowering these sites with clean energy resources, taking advantage of their existing connections to the grid.

In practice, however, the ability to transfer Capacity Interconnection Rights (CIRs) is outside of the State of Maryland's jurisdiction and is subject to PJM review [51]. In October 2024, PJM stakeholders approved a new CIR process, which aims to reduce processing time and is now expected to take approximately 10 months. The process allows a transfer request to be submitted either prior to the planned retirement of the existing asset or within three years of its deactivation. The review process includes the following phase (with their durations as expected by PJM): (i) Application Phase (60 days), (ii) Impact Study Phase (180 days), and (iii) Generation Interconnection Agreement (GIA) Negotiation Phase (60 days). PJM intends to prioritize applications sequentially, based on the order in which they are received. Furthermore, the replacement resource must connect to the same point of interconnection (the same voltage level and substation as the retiring generation) and must have a capacity equal to or lower than that of the retiring generation. The replacement resource can be of any eligible fuel type, including storage. Notably, the replacement generation resource is responsible for 100% of all identified network upgrades needed for the interconnection transfer. PJM tariff provisions implementing the new CIR process are expected to be filed with FERC in February 2025. Whether the proposed 10-month turnaround time is achievable, it is likely to be significantly shorter than the very long waiting times experienced presently in PJM's normal interconnection queue process.

The CSNA directs that a study be done of "*(t)he potential to develop clean energy resources on previously developed project sites*." Options include solar, wind, and (small-scale or modular) nuclear, with site-specific plans based on local conditions[5]. The legacy infrastructure at these sites, whether operational or retired, may retain salvageable value for repurposing into new generation projects. While some active plants may not be decommissioned in the near term, evaluating local renewable resource availability and development potential is crucial for long-term planning. These assessments, in part carried out by the Energy Industry Revitalization Working Group in parallel with this study, will inform decisions on whether repowering investments at these sites are necessary [52].

Table 4. Operating status of fossil-fueled power plants in Maryland

Generator resource type	**Total nameplate capacity**	**Weighted average operating years (2024)**	**Weighted mean operating years at retirement in U.S.[1]**
Coal	1599.2	34.9	50
Natural gas	6345.8	21.5	30~50 [2]
Petroleum liquids	1832.3	53.0	45

Note: [1] Weighted mean operating years at retirement is estimated from the Form EIA 860-2023 with generator-level specific information of the retired generators based on capacity weights.

[2] The weighted mean operating years of generators powered by natural gas depends on the technology type: 30 years for combined cycle technology, 40 years for combustion turbine and internal combustion turbine technology, and 50 yeast for steam turbine technology.

This section evaluates the potential of some power plants in Maryland for repowering with available solar and wind resources and, potentially, with biomass resources to support the state's decarbonization efforts. We first present a pre-screening of fossil-fueled generation sites in Maryland for potential suitability for renewable development (Section 4.1), and summarize the resource potential available for local renewables development across the sites (Section 4.2). Then we break down the potential for different resource types by considering the technical viability (Section 4.3) and summarize some additional considerations for repowering decisions (Section 4.4), which also includes a qualitative assessment for Small Modular Reactors (SMRs).

4.1. Site Pre-screening

The first step is to evaluate the operational status of Maryland's fossil-fueled power plants. We begin by filtering existing and retired in-state plants with a capacity of at least 100 MW[6] and an operational history exceeding 25 years. Applying these criteria to both active and retired facilities, 14 developed plant sites were identified for further assessment of alternative resource availability (Table 5).

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[5] Battery energy storage can be considered for repowering developed sites; however, it falls outside the working group's charge, which focuses specifically on the development of "*clean energy resources*."

[6] The threshold of 100 MW was selected as a reasonable size for a sufficiently large fossil-fueled power plant to be of economic value for deploying renewables.

For each site identified in Table 5, we carry out two evaluations. The first one evaluates the availability of local renewable resources, and the second one estimates the redevelopment potential for each renewable site.

Table 5: List of developed power plant sites for repowering potential assessment

Plant Name	perating apacity MW)	Retired Capacity (MW)	Area (Acres)	Plant Site Status
Brandon Shores	370.2	0	483 (Shared with Wagner)	Operating; retirement planned by 2028
Gould Street		103.5	5.6	Retired
Herbert A Wagner	22.5	136	See Brandon Shores	Operating + partially retired
Notch Cliff		144	Approx 2 (substation)	Retired
Perryman	92.3	0	704	Operating (includes 20 MW solar farm & undeveloped farmland, woodland)
Riverside (MD)		207.2	170	Retired
Westport		121.5	12.32	Retired
Vienna Operations	62	0	Approx. 50	Operating
Chalk Point Power	774	588	Approx 400 (of which switch yard 140)	Operating + partially retired
Dickerson Power	26	728	758	Operating + partially retired
Morgantown Generating Plant	30	1418	350	Operating + partially retired
AES Warrior Run Cogeneration Facility		229	Approx. 25	Retired [3]
Brandywine Power Facility	88.8	0	180 (of which 30 is for plant & facilities)	Operating
R Paul Smith Power Station		109.5	26	Retired

Data source: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

[1] Capacity and plant site status: Form EIA 860-2023 with generator-level specific information. Generators with the same plant code assigned by Form EIA 860-2023 are categorized as part of the same plant. Plants with the same latitude-longitude location are classified as the same plant site.

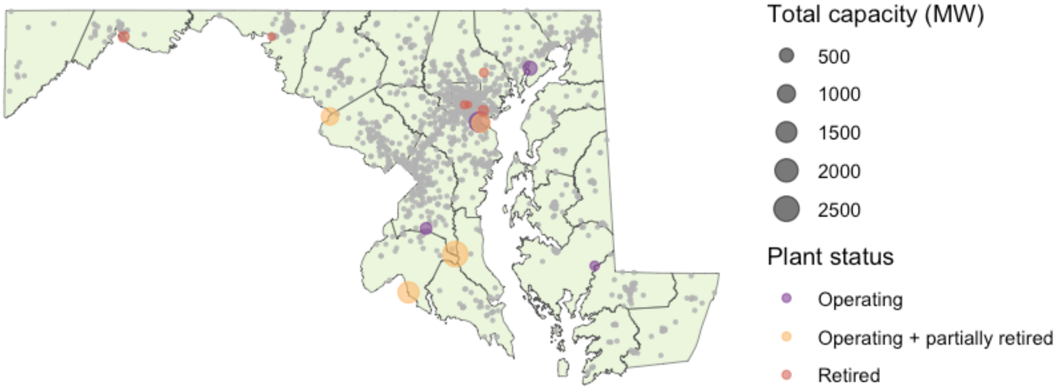
[2] Land area: Data is mainly collected from the reports of Maryland Department of the Environment and local news. Brandon Shores[53], Gould Street [54], Perryman[55], Riverside[56], Westport[57], Dickerson[58], Morganton[59], Brandywine [60], R Paul Smith [61] ; all approximate numbers estimated from Google Maps.

[3] According to the Preliminary Monthly Electric Generator Inventory (EIA 860M) published in Oct 2024, AES Warrior Run Cogeneration Facility retired in June 2024, while Morgantown Generating Plant also retired two units in the same month. R Paul Smith is a retired power station listed in the EIA 860M form (Oct 2024) instead of EIA 860-2023 Form.

4.2 Availability of Local Renewable Resources

To perform this evaluation for the sites in Table 5, we use land-use assessments from the Environmental Protection Agency's (EPA) RE-Powering America's Land Initiative [62]. The RE-

Powering Mapper evaluates renewable energy potential across 2,147 contaminated sites in Maryland, including brownfields, land restoration program areas, and Superfund sites. The RE-Powering projects (gray dots) form a dense network across the state, which overlaps spatially with the pre-screened power plant sites (colored dots), providing a valuable reference for exploring renewable energy potential at those sites (Figure 2).



Note: Gray dots are the brownfield sites in the RE-Powering Mapper of EPA

Figure 2: Spatial distribution of potential power plant sites for repowering

Assuming minimal variations in slope and terrain within short distances, the renewable energy potential at power plant sites is considered similar to nearby RE-Powering sites. To refine estimates, resource availability for each power plant site was inferred using an inverse distance weighting method based on the five nearest RE-Powering sites. Inverse distance weighting can interpolate the unknown values of a given plant site location from the known values of the surrounding RE-Powering locations, with more details introduced in Appendix 1.

1. Solar: Solar availability, measured as global horizontal irradiance (GHI), ranges from 4.0 to 4.4 kWh/m² per day, classifying all 14 sites within the moderate solar resource category [63].
2. Wind: Wind availability varies significantly across the sites, with speeds ranging from 3.4–5.3 m/s at 40m, 4.0–6.5 m/s at 80m, and 4.2–6.9 m/s at 100m. These values classify the sites as Class 3 (for winds less than 7.5 m/s) [64]. Based on GE's technical specifications for onshore wind turbines (hub heights of 80–100m), four sites qualify for the IEC-III low wind class, with wind speeds exceeding 6 m/s at 80m [65], [66].
3. Biopower: Local biopower availability depends on location and is measured by annual resource availability within a 50-mile radius[7]. Consistent with the definition of the RE-Powering Mapper of EPA, cumulative biopower sources include residues from urban wood waste, forestry, as well as primary and secondary mills, while biorefinery wastes are supplied from crops. Ten of the 14 sites can theoretically – which is not necessarily economic -- harvest more than 1.8 million tons of local biopower fuel annually—which has a relatively low equivalent power yield (e.g., comparable to ~64.5 MW) (Figure 3). More feedstock could be available from urban wood waste for biopower use; however, further

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[7] 50-mile radius, set by the RE-Powering Mapper of EPA, is a typical maximum distance by the rule of thumb to economically obtain the local bio-power resources, with a consideration of transportation costs.

development may be constrained economically and due to other considerations for societal feasibility. For example, whether combustion of solid waste can continue to be eligible to meet Renewable Portfolio Standard requirements may be considered by the next session of the Maryland General Assembly.

Figure 3 provides a detailed visualization of the resource variability across sites, highlighting key insights into each resource type.

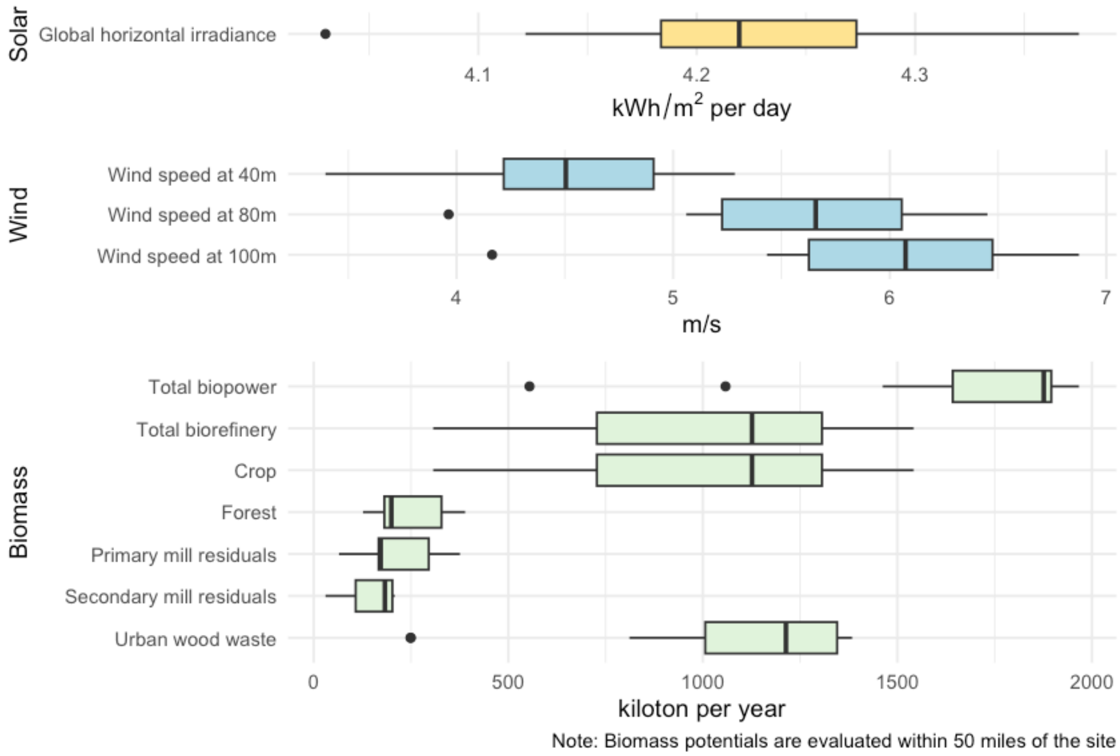


Figure 3. Boxplot of resource availability in vicinity of developed plant sites

Notes:

[1] Total biopower is the aggregation of all woody biomass types, including residues from forest, primary and secondary mill, as well as urban wood waste, which follows the definition used in the RE-Powering Mapper of U.S. EPA [67].

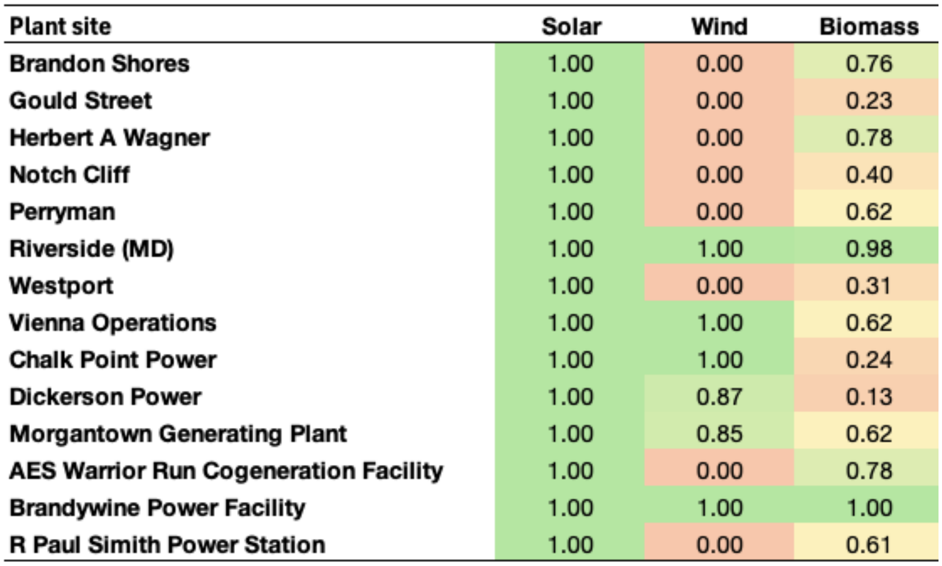
[2] Resource availability estimates of the plant sites are interpolated from the resource information given in RE-Powering Mapper Data of EPA based on inverse distance weighting method [67]. More details about the inverse distance weighing method are introduced in Appendix 1.

4.3. Redevelopment Potential by Resource Type

Redevelopment potential is assessed as whether a developed plant site shows potential for repurposing with a particular resource type. This potential is expressed as a percentage, summarizing whether the five nearest RE-Powering sites indicate such technical potential, calculated using the inverse distance weighting method (Appendix 1). For each RE-Powering site, the potential data is binary, reflecting whether the site has resource potential based on both resource availability and technological constraints, such as terrain and land area. If a nearby RE-Powering site shows potential for solar capacity development, the associated developed plant site is also likely to exhibit high potential for solar energy repowering.

All selected developed power plant sites demonstrate redevelopment potential for PV energy repurposing, although some locations have much more land area than others, while wind and biomass options are viable for only a limited number of sites. When exploring repurposing options for each developed plant site, all sites support at least one option (PV). Using 0.75 as a threshold (green-shaded in Table 6) to indicate high redevelopment potential, seven of the 14 plant sites can develop customized repurposing plans involving one technology (PV). Riverside Generating Station and Brandywine Power Facility are the only two sites displaying redevelopment potential for all the resource types considered.

Table 6: Probability index of technical energy potential by resource type across plant sites



Plant site	Solar	Wind	Biomass
Brandon Shores	1.00	0.00	0.76
Gould Street	1.00	0.00	0.23
Herbert A Wagner	1.00	0.00	0.78
Notch Cliff	1.00	0.00	0.40
Perryman	1.00	0.00	0.62
Riverside (MD)	1.00	1.00	0.98
Westport	1.00	0.00	0.31
Vienna Operations	1.00	1.00	0.62
Chalk Point Power	1.00	1.00	0.24
Dickerson Power	1.00	0.87	0.13
Morgantown Generating Plant	1.00	0.85	0.62
AES Warrior Run Cogeneration Facility	1.00	0.00	0.78
Brandywine Power Facility	1.00	1.00	1.00
R Paul Simith Power Station	1.00	0.00	0.61

Data: Form EIA 860-2023 with generator-level specific information. Generators with the same plant code assigned by Form EIA 860-2023 are categorized as part of the same plant.

Note: Probability is colored based on the values: from the highest with green colors and the lowest with orange colors.

Based on the plant site area (from Wikipedia and other sources), existing facilities that will remain in operation in the future, and assumptions about solar capability per acre, we can estimate the potential PV development for the sites listed in Table 6. We assume conservatively that half of a retired plant site or unoccupied area might be realistically devoted to solar development, with a maximum capacity of 0.12 MW/acre.[8] Since the number of acres available for solar development are highly approximate, and depend on particular site characteristics and other uses that a site might be devoted to now or in the future, we report a total across all power plants and merely conclude that larger sites are more promising than smaller ones, in part to allow for a buffer between neighboring developments and a new solar plant. The total acreage in Table 5 is 3160

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[8] Based on solar development experience in Maryland. For instance, the Rockfish PV development occupies 83 acres and has a nominal capacity of 10 MW (AC), while the proposed Snow Hill solar farm would have occupied 125 acres and produced up to 15 MW. See MPPRP, Maryland Power Plants and the Environment (CEIR-21) for other examples [68].

acres (slightly less than 5 square miles). If half is devoted to new solar development, this would result in approximately 200 MW (AC) of peak capacity at 0.12 MW/developed acre. This amount of development is equivalent to about 1/3 of the total of 627 MW of utility-scale solar capacity reported for Maryland in September 2024 [69]. For reference, the smallest operating fossil-fueled power plant in Table 5 has power capacity of 162 MW (Vienna Operations) and the largest operating fossil-fueled power plant in Table 5 has power capacity of 1370.2 MW (Brandon Shores).

4.4. Additional Considerations

As more plants approach retirement, it is essential to conduct system-level repowering studies in addition to site-specific resource assessments. An important factor in these studies is that the decision to retire an existing power plant lies solely with the generator owner but remains subject to PJM's review. To retire a generator in PJM, the owner must submit a formal notification to PJM, providing at least 90 days notice, a reason for retirement (e.g., economic, mechanical, regulatory, or environmental constraints), and a proposed deactivation date. Once this notification is received, PJM conducts a reliability analysis to assess whether the requested retirement would impact reliability of the grid. If no issues are identified, the retirement can proceed as planned; however, if reliability concerns arise, PJM may propose solutions, such as transmission upgrades, power flow re-routing, or temporary continued operation under a Reliability Must-Run agreement. Finally, in addition to PJM's approval, generator retirement may require coordination with state and federal agencies to meet regulatory, financial, and environmental obligations. This includes addressing market impacts with FERC and ensuring site remediation and compliance with environmental standards.

Given the complexity of the retirement process, a system-wide assessment can provide valuable insights as to the ratepayer cost, emissions impacts, and reliability implications of different transition pathways for generation owners, utilities, policymakers, and other stakeholders under different supply, climate, and load growth scenarios. In particular, integrated consideration of alternative pathways and their impacts can inform public discussions as well as legislative and regulatory decisions by policy makers and investment decisions by market participants. System-wide assessments can help regulators and stakeholders to understand how capacity inadequacy outage risks can be mitigated by identifying and comparing relatively attractive alternatives regarding the timing of retirements, repowering projects and new interconnections to prevent resource inadequacy problems, such as what has occurred in 2024 (e.g., the postponed retirement of Herbert A. Wagner and Brandon Shores Power Plants [70]). Additionally, access to renewable resources may be spatially and temporally constrained, such as the annual availability of biopower in the state or spacing requirements for wind projects. A system model can help identify combinations of resource and grid reinforcement investments that interact effectively to address resource adequacy issues in a cost-effective and sustainable manner across a region, which can provide information on benefits and costs for Maryland's, helping to make its participation in PJM and other regional processes more effective.

In summary, solar is a promising resource for repowering Maryland's aged plant sites, with wind and biomass being viable for select locations, subject to their continued eligibility for Maryland's RPS. Beyond renewable resources, SMRs are also being considered as a potential repowering technology due to their firm and clean generation output. However, SMRs remain in early development and require specific geological conditions, which most Maryland plant sites may not meet (see Section 5 for details). For the purposes of this report, despite the optimism of some analysts [71], we assume that technology development and permitting will not be possible in Maryland at a significant scale before the late 2030's as the ability of SMRs to be deployed at a competitive cost and public acceptability become more established. However, for time horizons beyond the late 2030's, SMRs may become an economically and regulatorily viable low-emissions technology that could be coordinated with the retirement of fossil-fuel generation to minimize the cost of stranded transmission assets and interconnection delays. The International Atomic Energy Agency also concludes that large-scale deployment of SMRs "*will need a degree of regulatory convergence*" internationally and warns that "*without some degrees of concrete collaboration where we can leverage what others are doing, the business model of modularity and flexibility is simply not going to work*." For future reference, some optimistic assessments suggest that upon becoming commercially available SMR units will take 8-9 years to be deployed, including (i) pre-application (2-3 years), licensing application (3 years) and manufacturing construction (3 years) [72]. Furthermore, there could be further improvements in delivery times due to the likely overlap (1-2 years) between the manufacturing and licensing stages and due to the scalability benefits (e.g., for a series of SMR units to be deployed at a single location, the deployment time is estimated to be potentially 6-8 years rather than 8-10 years).

5. Lifespan and Viability of Clean Energy Power Generation Facilities

As of 2023, 3.3 GW of generating capacity in Maryland comes from non-fossil resources, accounting for one-quarter of in-state capacity and over half of in-state electricity generation. However, by the late 2030s, some of these resources—such as biomass, hydroelectric, and nuclear plants—will likely face operational challenges as they may near the end of their licensed or technical lifetimes, necessitating further permitting and potentially investments. Therefore, proactive investments into expanding renewable energy resources such as wind, solar, and energy storage systems will be essential to maintain and grow Maryland's clean energy capacity. Accordingly, the CSNA directs that a study be done to estimate "*the lifespan and viability of energy facilities in the state that do not emit Greenhouse Gas*".

Table 7 summarizes the technical lifetimes of various existing and prospective technology types. The existing assets include three plants that utilize biomass for at least a portion of their fuel (Wheelabrator solid waste combustion facility, Eastern Correctional Institute[9], and Montgomery County Resource Recovery Facility), certain hydroelectric turbines (Deep Creek and portions of Conowingo), and the Calvert Cliffs nuclear power plant.

To assess the feasibility of various clean energy technologies in Maryland, we address the following considerations:

- Section 5.1 "Resource potential," which considers physical constraints and "Technical potential," which accounts for technological and land-use limitations,
- Section 5.2 "Economic potential," determined by the affordability of technology and fuel, and
- Section 5.3 "Regulatory potential," shaped by policies and regulations. [73]

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[9] As of October 2024, the Eastern Correctional Institute is listed as a "Wood/Wood Waste Biomass" facility on the EIA 860 form. However, it is currently undergoing renovations, including a combined heat and power (CHP) upgrade and a fuel conversion to natural gas. The project is anticipated to be completed in early 2025.

Table 7: Deployment status and lifetime of clean energy power plants in Maryland.

Generator resource type	Operating capacity (MW)	Weighted average operating years (2024)[1]	Technical lifetime (years)[2]
Solar	590.9	5.4	30
Wind	190.0	12.1	30
Water	550.8	81.6	100
Storage	13.7	7.7	30
Biogas	13.6	14.6	45
Biomass	136.1	33.9	45
Nuclear	1850.4	48.0	60

Notes:

[1] "Weighted average operating years (2024)" is estimated from the Form EIA 860-2023 with generator-level specific information on the number of operating years based on capacity weights. Here is the calculation for operating years for each generator: Operating years = 2024 – Initial operating year.

[2] Technical lifetime data is from the Annual Technology Baseline 2024 from National Renewable Energy Laboratory (NREL).

5.1. Resource & Technical Potential

We note that due to different characteristics and physical principles underlying power generation it could be difficult to compare different technology types on par with one another.

Solar Energy: Maryland's solar potential averages 4.8 kWh/m² per day, similar to the national average. The strongest potential is in the Southern and Eastern Shore Regions (up to 5.1 kWh/m²), with the lowest in the Western Region (4.3 kWh/m²).

Wind Energy: Most areas have Class 2 wind resources (low-grade), but high-quality Class 3–5 wind potential exists in the Western and Eastern Shore Regions.

Biomass Energy: Maryland's biomass resources, including urban wood waste, landfill, and crop residues, are below the national average but significant in the Capital Region, which ranks in the top 40% nationally.

Hydro Energy: Maryland's hydropower potential is limited, with a maximum of 59 GWh/year found near rivers in the Western and Central Regions (~121 km2), ranking in the top 20% nationwide. Environmental considerations render development of run-of-river or pondage-based hydropower unlikely; pumped storage, however, may be a possibility where construction of off-stream upper reservoirs with a significant head is feasible.

Nuclear Power: While Maryland lacks uranium reserves, suitable areas for advanced nuclear projects (e.g., SMRs) are identified in the Southern and Eastern Shore Regions using safety and geological criteria. Note that to identify these sites, we screened out the ineligible areas with the Siting Tool for Advanced Nuclear Development (STAND) developed by Fastest Path to Zero Initiative by applying some basic filters on unsafe shutdown earthquakes levels, faults lines, landslide hazard, and high population density (> 500 per square-mile).

5.2. Economic Potential

Economic potential measures the cost of utilizing alternative energy resources through specific technologies. A common metric is the Levelized Cost of Electricity (LCOE), which represents the average cost of generating one MWh of electricity, including capital, operation, and maintenance expenses over a plant's lifetime [74]. However, it is widely recognized that LCOE metrics do not correctly account for dispatchability, and so an optimal mix of generation types to meet time varying demand will include multiple technologies with widely varying LCOEs. The least cost mix of supply types, storage, and demand-side management is best addressed by capacity expansion models that account for time-varying demands, flexibility and dispatchability needs, operating reserves, and various system limits such as fuel and transmission. (This issue was discussed in the context of storage valuation in Section 1.2)

Although LCOE has significant limitations, it is a convenient index to communicate cost trends over time and across technologies. LCOE varies significantly across technologies and regions. Some recent values are the following [75]. In the U.S., solar and onshore wind are among the most cost-effective options, with average LCOEs of $36–40/MWh. In contrast, hydroelectric, biomass, and advanced nuclear power have higher averages of $64/MWh, $90/MWh, and $88/MWh, respectively. Some technologies, like onshore wind, hydroelectric, and biomass, also exhibit greater regional cost variability ($30–60/MWh) due to resource availability differences (Figure 7).

Hybrid systems combining generation with battery storage can enhance economic potential by reducing costs and improving efficiency. For instance, pairing solar energy with batteries lowers storage costs from $129/MWh to $49/MWh—a 60% reduction—by mitigating resource intermittency and curtailment (Figure 4).

Grid connection costs also impact economic potential, often depending on a site's proximity to existing infrastructure. New projects are typically sited near transmission and distribution networks unless large-scale revenues justify additional interconnection costs.

For example, Maryland's Smart DG+ tool identifies potential solar development area based on the proximity to the power grid. Through the screening tool, land area is considered suitable for utility-scale solar development after excluding the areas associated with airports, flood zones, protected zones, and high population[10]. Expanding the screening range from 1 to 2 miles increases the available area and theoretical solar capacity by 140%, primarily due to the larger proportion of unrestricted or protected-use areas within the 1–2 mile range compared to the 0–1 mile range. Similarly, extending proximity to transmission lines from 2 to 4 miles doubles potential capacity to 127 GW if the average facility footprint is low —over half of Maryland's technical potential[11] for utility-scale solar.

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[10] Besides the grid infrastructure proximity, specific screening factors on the land availability include airport and landing strip (with 3-mile buffer), critical areas (except for solar), federal properties, high-density residential areas, urban areas with limited open space, floodplains, county parks, Forest Conservation Easements, Maryland Environmental Trust Easements, wetlands of special state concern (with 100-foot buffer), National Register of Historic Places, private conservation properties, and rural legacy property.

[11] Technical potential for utility-scale solar is estimated to be 213.2 GW in Maryland, based on technical potential annual generation (122,000 - 640,000 GWh/year.) in the State and Local Planning for Energy (SLOPE) tool by NREL [77], and the average capacity factor of utility PV (24%) from NREL's Annual Technology Baseline 2024 [78].

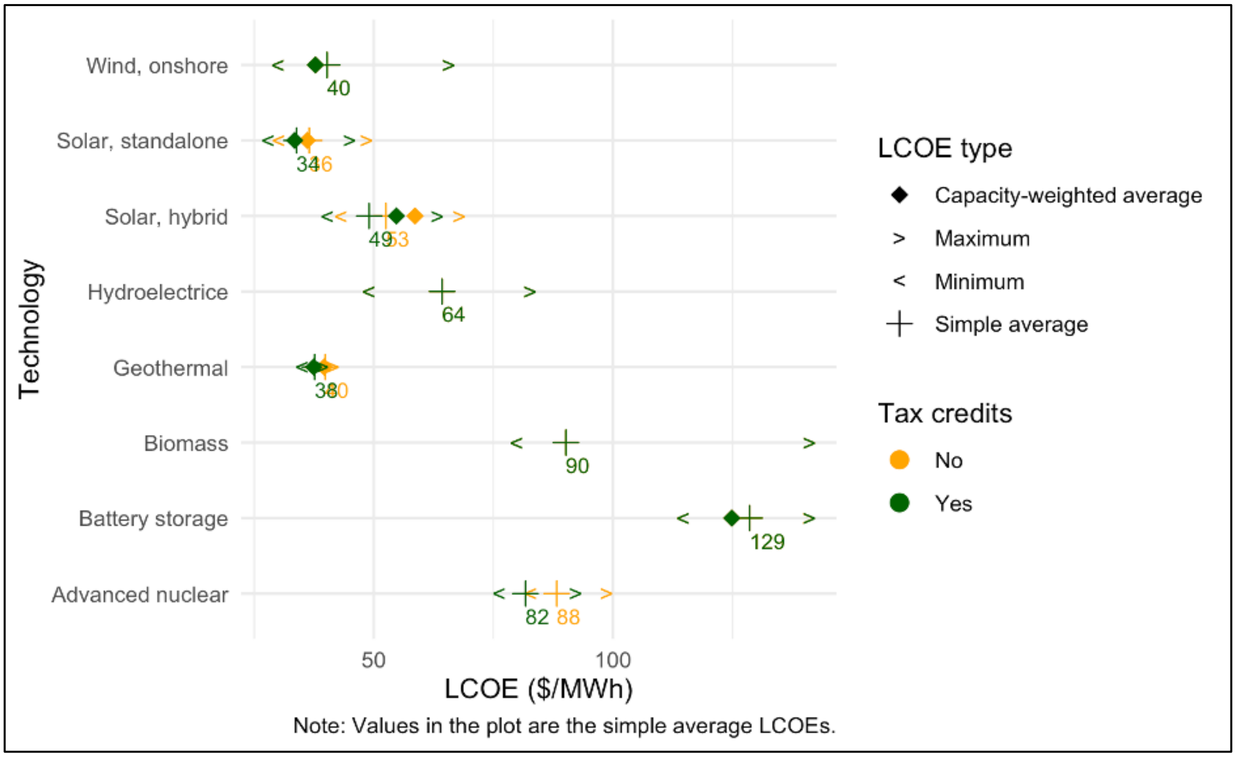

Figure 4: Estimated range of LCOE by technology across the U.S.

Note: Values displayed in the plot are the simple average LCOEs. The unit of LCOE is 2021 U.S. dollars per MWh. If the technology shows only LCOE under tax credits, this indicates the LCOE of with and without tax credits stays the same.

Data source: EIA. 2022. Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022 [76].

However, the estimated theoretical potential depends on the actual MW/acre values, a more realistic estimate in Maryland has a moderate footprint of 7 acres per MW[12], which can reduce the potential capacity by 30% (see the moderate facility footprint and notes in the Table 8). The new solar projects under review have an average footprint ratio of 5.78 acres/MW[13], which also indicates promising utility-PV potential in Maryland. Furthermore, the calculations based on transmission distance do not account for the need for substations for interconnection, which are impractical or expensive to be retrofitted for small PV plants on high voltage lines. By comparison, EPA estimate a lower potential capacity of 13.2 GW in total utility-PV installation on the RE-Powering projects sites in Maryland, highlighting that there may be significant unrecognized opportunities for solar installations on state land near existing power grid infrastructure (Table 8).

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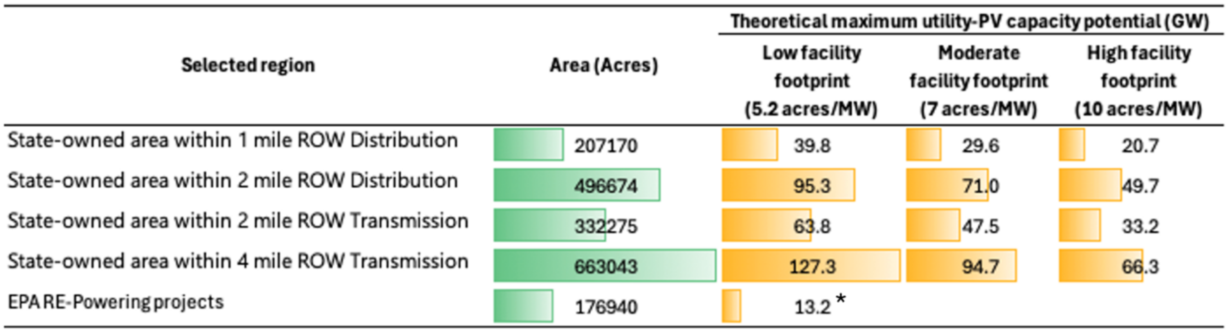
[12] We note that additional information provided to the authors by the Maryland Department of Natural Resources indicates that this footprint can actually be lower (5 acres/MW) and tends to decrease over time.

[13] Maryland Public Service Commission website listed proposed solar PV projects with a total capacity of 142.4 and a total area of 823 acres (last updated on November 12, 2024) [79]. We also note that additional information provided to the authors by the Maryland Department of Natural Resources indicates that the latest applications received by them equals 4.7 acres/MW.

Table 8: Economic potential of solar with grid infrastructure proximity



Selected region	Area (Acres)	Theoretical maximum utility-PV capacity potential (GW)		
		Low facility footprint (5.2 acres/MW)	Moderate facility footprint (7 acres/MW)	High facility footprint (10 acres/MW)
State-owned area within 1 mile ROW Distribution	207170	39.8	29.6	20.7
State-owned area within 2 mile ROW Distribution	496674	95.3	71.0	49.7
State-owned area within 2 mile ROW Transmission	332275	63.8	47.5	33.2
State-owned area within 4 mile ROW Transmission	663043	127.3	94.7	66.3
EPA RE-Powering projects	176940	13.2 *		

Data source: The table is compiled by the JHU team using the data from Smart DG+ for the state-owned areas (first four lines of the table) and the EPA Re-powering projects data (the last line of the table). Smart DG+, sponsored by Maryland Power Plant Research Program (PPRP), is a screening tool to search for eligible and economic renewable energy projects considering the proximity to existing grid infrastructure [80]. The acre area is an aggregation of the scattered available areas after applying the screening filters within infrastructure proximity and outside some critical and protected zones (See footnote 9 for more details).

Notes :* indicates the estimates of the total utility-PV capacity potential in Maryland is a different calculation approach for the brownfields in EPA (with more details in Note 3).

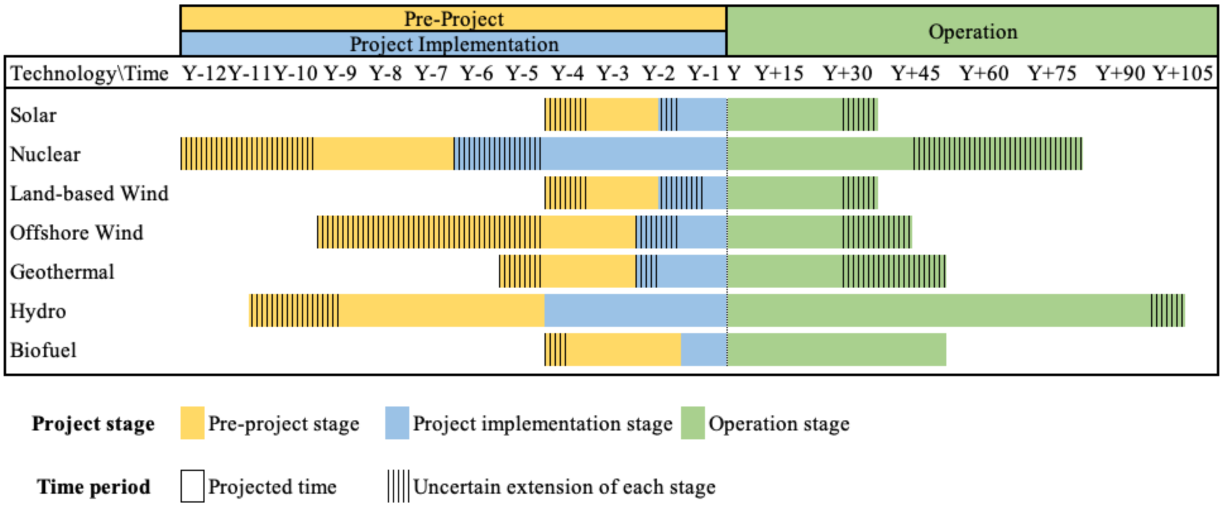
[1] In the “Selected Region” column, ROW refers to the right of way.[2] For open space state-owned area, theoretical maximum PV capacity potential is calculated based on the area-to-capacity conversion factor. The conversion factor, 5.2 acres per MW, is inferred from an NREL study [73], which includes an assumption on utility-PV potential estimates based on land area in Maryland and still considers a low facility footprint level. The actual solar developments in Maryland have a ratio of 5~7 acres per MW [81], hence 7 acres/MW being used in the moderate facility footprint. In the high facility footprint column, 10 acres/MW is a generic number for sensitivity tests, but such footprint can also be found in some proposed PV sites of Maryland: Morgnec Road Solar from Urban Grid, and Biggs Ford Solar from Coronal [82].[3] In the EPA RE-Powering projects, the total utility-PV capacity potential is an aggregation from EPA’s capacity estimates on each project that is suitable for utility-PV installation (≥ 35 acres and within 10 miles to the transmission lines and to the graded roads). The solar capacity potential is inferred based on the area of each site and the land requirement of 6.9 acres per MW. If including the distributed PV for smaller sites, total potential capacity to install on the RE-Powering projects is 14.7 GW.

5.3. Regulatory Potential

Regulatory potential evaluates the socio-economic factors that influence the adoption of energy technologies, including policy impacts and regulatory constraints. For example, regulatory potential can be significantly affected by time-intensive processes such as federal environmental permits and impact statements, state government certificates of public convenience and necessity, and logistical hurdles. Once a new energy project passes a techno-economic feasibility analysis, it must navigate a series of permitting and regulatory steps. These include siting, procurement, construction, inspection, interconnection, and operational eligibility—steps that collectively determine the project's timeline for commercial operation [83]. Importantly, the interconnection of new generation sites and transfers of interconnection rights from existing generation sites (See Section 4.4) is not in State of Maryland’s jurisdiction and requires approval by PJM. On the one hand, PJM realizes the importance of interconnecting additional generation to support anticipated load growth and has recently proposed to speed up its interconnection process for a limited number of generation projects (e.g., “reliability resource initiative” [84]). On the other hand, this new process, which is currently under review and is yet to be filed with FERC as of December 2024, has sparked controversary as it may give a preferable treatment to a limited number and types of generators and could be discriminatory against other generators in the queue [85].

The total time required for these processes, referred to as “lead time,” can range from several years to over a decade and is influenced by factors such as construction schedules, supply chain dynamics, interconnection status, and government efficiency. Deployment of new energy projects will typically go through two stages: the Lead Time Stage and the Operation Stage. The Lead Time Stage consists of the activities in the Pre-Project Stage, involving feasibility and interconnection studies, regulatory approvals, and permitting, as well as the tasks during the Project Implementation Stage, encompassing detailed engineering, procurement, and construction. Total projected time spent on each stage could be extended with possible delays or schedule adjustments due to unforeseen circumstances, namely “Transitional and Uncertain Time” and represented the shaded areas in Figure 5.

Figure 5: Deployment timeline and lifespan for prospective alternative energy technologies



Data from: EIA, 2022, Assumptions of the Annual Energy Outlook 2022: Electricity Market Module [86].
Note: Note different scales on the pre-project/project implementation (12 years) and operations sides of the figure (up to 105 years). Estimates are based on conventional nuclear technologies and do not account for the potential deployment time of SMRs which is uncertain at this time.

Solar [87], [88], [89], land-based wind [90], and biofuel [91], [92] projects typically have the shortest lead times, ranging from 3 to 4 years. While technologies like geothermal plants and offshore wind projects generally require 4 to 5 years or more, depending on their complexity and siting requirements [93]. Offshore wind projects, in particular, often face significant uncertainty during the pre-project stage, including lengthy permitting processes, plan reviews, and lease submissions, which can take up to 5 years with considerable variability [94]. Hydroelectric projects have some of the longest lead times, often exceeding 10 years, depending on the project's size and siting challenges. The pre-project stage for hydroelectric projects is especially extensive and uncertain, as it involves processes such as permitting, license applications, and the timing of critical studies, including geotechnical investigations, topographical and bathymetric surveys, physical hydraulic modeling, and flood studies [95], [96]. Nuclear power has the longest lead time [97]. In the US, only three nuclear units have been constructed since 2000: Watts Bar Unit 2, completed in 2016, and Vogtle Units 3 and 4, completed in 2023 and 2024, respectively. Currently, there are no nuclear projects under construction. For reference, Vogtle Units 3 and 4 began construction in 2009 and took 14 and 15 years to complete, in part due to the challenges associated with the first-of-a-kind deployment of the AP1000 reactors in the United States. By contrast, international experience suggests that nuclear power plants can often be built in seven years or less on average, with some projects completed in under five years and others taking up to 11 years [98]. Although proponents of small modular power plants hope for shorter (on average) lead times for small plants, taking advantage of both simpler engineering and economy of scales (Figure 5) [98].

6. Summary & Recommendations

This report describes possible choices for and actions necessary to develop an informed energy policy for the State of Maryland to ensure an efficient, affordable, reliable, and sufficient electricity supply for all consumers and to comply with the State's clean energy goals. This report underscores the importance of a forward-looking energy planning approach in Maryland, while considering complex interdependencies with PJM and neighboring states. By addressing uncertainties, leveraging a diverse set of generation technologies, and coordinating with PJM, the state can position itself to meet future electricity demand, while achieving its clean energy goals and achieving the desired level of reliability for electricity supply.

By examining existing power outage profiles (Section 2), the report concludes that maintaining the current level of reliability will require that regulators, market participants, and stakeholders undertake proactive, system-wide analyses of alternative transition pathways in order to inform policy processes, planning of grid infrastructure, and market investments in resources. Such analyses must comprehensively account for anticipated load growth, changes in the supply mix (including new interconnections, power plant retirements, and potential repowering on existing sites), evolving state and federal policies, planning by PJM and neighboring ISOs, and interactions with decisions by other states within and outside of PJM. A critical consideration is the State of Maryland's limited influence over transmission network planning and the evolving rules governing PJM's planning processes.

Given the uncertainty surrounding supply mix changes, load growth, and policy shifts, informed system-wide analyses will necessitate the development of long-term planning scenarios. These scenarios must consider the individual drivers of these factors, their uncertainties, and their potential correlations. By incorporating these elements, Maryland can minimize outage risks and optimize the modernization of both its distribution and transmission grids (Section 3) in a way that is robust to possible changes in technology, policy, and economic drivers. Analysis presented in Sections 2 and 3 underscores the importance of exploring a diverse set of technological options—including storage, DERs, microgrids, wind, solar, demand-side management, and potentially biomass and SMRs to ensure that resource and grid development pathways are identified that are efficient, sustainable, and reliably meet consumer needs, in particular to critical loads.

Section 4 provides a quantitative assessment of re-use of existing generation sites where present facilities may face retirement due to economic, regulatory, or other factors. Solar emerges as the most viable supply option, offering the best economic and resource potential for most potential sites, while wind and biomass also present opportunities where resources are favorable. However, as highlighted in this section, the success of site re-use efforts is highly sensitive to PJM's ability to process interconnection requests in a timely manner—an issue currently under review. Complementary to Section 4, Section 5 summarizes the economic, technical, and resource potential for deploying clean energy resources. Similar to re-using decisions discussed in Section 4, this analysis emphasizes the importance of PJM approvals in unlocking the deployment of this capacity. Both Sections 4 and 5 also highlight the need for additional consideration of SMRs. These assets have the potential to deliver firm, low-carbon electricity; however, they remain in the early stages of development, with uncertainties surrounding their technical performance and economic feasibility.

The findings of this report are consistent with the Energy Resilience and Efficiency Working Group (EREWG) Final Recommendations passed on September 10, 2024, and highlight the following for future consideration:

- The State of Maryland will benefit from a comprehensive, state-wide modeling and analysis framework that allow for consideration by stakeholders, market participants and regulators of alternative pathways for the energy transition under different policy, economic, and technology scenarios. These scenarios should account for both in-state and out-of-state conditions to achieve state reliability and clean energy goals, while assessing how these choices translate into total costs and consumer impacts.
- The recommended modeling and analysis framework should address immediate and mid-term state needs and remain adaptable to evolving priorities over time. Some state needs identified in this report and by the Working Group include:
    - Study transmission line reconductoring and evaluate the ability of non-wire alternatives for transmission expansion (e.g., storage).
    - Study the interconnection of planned Offshore Wind projects and assess whether additional in-state transmission capacity is required.
    - Study land availability and environmental-social-economic tradeoffs in identifying sites suitable for solar energy and energy storage development.
    - Analyze potential impacts of distribution system decisions (including distributed resources) on transmission system operations and reliability.
    - Assess the feasibility of SMRs for deployment within the state, particularly on former or soon-to-retire generation sites.
- To support the assessment of state needs and development of integrated analysis capabilities framework, the State of Maryland will benefit from continued investment in a user-friendly, transparent policy and grid evaluation models and software for state-wide energy projections and pathway evaluations. This software should:
    - Account for time horizons regarding the commercialization of energy technologies (e.g., storage, wind, solar, SMRs).
    - Evaluate when these technologies may become available for deployment, including potential delays.
    - Provide detailed cost and reliability impacts under various planning scenarios.
    - Include associated analyses of greenhouse gas emissions, ratepayer impacts and affordability, equity considerations, and progress toward clean energy goals.

Appendix 1. Inverse Distance Weighting

This Appendix summarizes the method used in Section 4 to assess suitability of re-using different potential sites for clean resource development.

Inverse distance weighting method, also known as Shepard's interpolation, is a deterministic method to interpolate unknown values within a specified search distance and scattered point values [99]. In this study, we can obtain the average resource potential of the developed plant site i by giving weights to the five nearest RE-Powering project sites:

$$w_{i,n} = \frac{1}{d\left(s_i,\ \ s_{i,n}\right)^2}, \forall n \in [1,5]\ the\ nearest\ five\ RE - Powering\ Project\ sites$$

and by taking the weighted average resource availability (RA) for plant site i:

$$RA_i = \frac{\sum_{n=1}^{5} w_{i,n}\ * RA_{i,n}}{\sum_{n=1}^{5} w_{i,n}}$$

The distance is calculated as the Euclidean distance between two points using their longitude and latitude coordinates. These calculations were performed with the "idw" command in an open-source R package named "phylin" on spatial interpolation. [100]

Consider a solar resource, for example. The developed plant site first searches for the five nearest sites among all RE-Powering projects (see Table A1 below). Given the distance and solar availability information listed in the table, the estimated solar availability is $4.26\ \mathrm{kWh/m^2\ day}$, based on the formula below:

$$\frac{0.01 \times 4.3\ +\ 0.044 \times 4.2\ +\ 0.0011 \times 4\ +\ 0.0004 \times 4.6\ +\ 0.0002 \times 4.5}{0.01\ +\ 0.0044\ +\ 0.0011\ +\ 0.0004\ +\ 0.0002} = 4.26\ \mathrm{kWh/m^2\ day}$$

Re-development potential for each site, measured in probability, is also estimated using inverse distance weighting method. RE-Powering Mapper concluded whether each site has development potential by resource type including solar, wind, and biomass, based on the resource availability and terrain characteristics. The re-development probability of the plant site is the weighted average calculated based on such binary information of the surrounding RE-Powering project sites. The redevelopment potential (RP) for the plant i is formulated as below.

$$RP_i = \frac{\sum_{n=1}^{5} w_{i,n}\ * RP_{i,n}}{\sum_{n=1}^{5} w_{i,n}}$$

In the given example, the probability of the plant site developing biopower through wood biomass is 0.66.

$$\frac{0.01 \times 1\ +\ 0.044 \times 0\ +\ 0.0011 \times 0\ +\ 0.0004 \times 1\ +\ 0.0002 \times 1}{0.01\ +\ 0.0044\ +\ 0.0011\ +\ 0.0004\ +\ 0.0002} = 0.66$$

Table A1. Example of inverse distance weighting method on resource availability and potential

Nearest RE-Powering projects	Distance (km)	Inverse distance weight (1/D^2)	Solar availability (kWh/m^2)	Biomass Development Potential (1=Yes, 0=No)
RE-Powering_Site1	10	0.01000	4.3	1
RE-Powering_Site2	15	0.00444	4.2	0
RE-Powering_Site3	30	0.00111	4	0
RE-Powering_Site4	50	0.00040	4.6	1
RE-Powering_Site5	70	0.00020	4.5	1

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