# The *Solar Futures Study* Study

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## I. INTRODUCTION

The Solar Futures Study (SFS) is a report considering the role of solar energy in the transition of the United States to a carbon-free electric grid. The study uses a mathematical programming model of the electric power sector called Regional Energy Deployment System (ReEDS) to model three potential scenarios for the growth of solar power: a reference business as usual scenario, a decarbonization scenario, and decarbonization with widespread electrification of end uses. The findings include insights on the extent and rate of adoption of solar technologies that will be needed, the amount of investment and new technology required, and the social and financial realities of the energy transition. The SFS also presents significant technical challenges along with potential solutions. The SFS was produced by the U.S. Department of Energy Solar Energy Technologies Office (SETO) and the National Renewable Energy Laboratory (NREL). This paper will give an overview of the modeling done for the SFS and present challenges discussed in the SFS and their solutions.

## II. THREE SCENARIOS

The three scenarios used by the model are referred to in the SFS as Reference, Decarb, and Decarb + E. The Reference scenario takes current energy policy and technology trajectories into account but lacks a concerted comprehensive effort to reduce carbon emissions. Even without this concerted effort, solar capacity in this scenario increases sevenfold by 2050, driven by established market forces and continuing technological advancements. In the Decarb scenario, the grid reaches 95% reduction of 2005 emission levels by 2035 and complete carbon neutrality by 2050. Decarb + E takes these constraints one step further by assuming that the grid will need to absorb an increased load of 30% by 2035 and an additional 34% by 2050 in the form of end uses that are currently supplied by non-grid fossil fuel energy sources such as building heat load met by natural gas. Illustrated in figure 1, in both decarbonization scenarios, solar supplies 45% of electricity demand, about the same is supplied by wind, and the remainder is met by a mix of nuclear, hydropower, biofuel, and hydrogen.

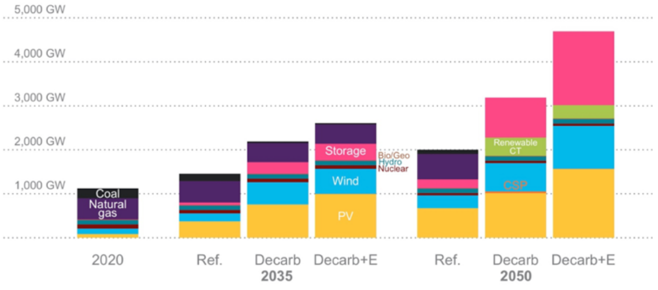

*Figure 1 (from [4]). The breakdown of capacity of by technology in 2020, 2035 and 2050 in the three scenarios.*

## III. POWER SECTOR MODELING

How exactly does the SFS come to these conclusions? ReEDS, NREL's power sector capacity planning model, does the heavy lifting. Given a set of input assumptions about cost projections and constraints, ReEDS simulates the progression of generation, transmission, storage, and end-use demand. The model solves simultaneous optimization problems using the GAMS modeling platform. At its core, there is a supply module linear program that minimizes the cost of power sector investment and operation, a demand module linear program that maximizes end-use device investment and operation, and a variable renewable energy (VRE) module that estimates capacity credit and curtailment.

In the model, the power market is separated into 134 geographic balancing areas, each of which must optimize its supply and demand in 17 time slices per year. The regions are connected with a representation of the transmission network that consists of the current network plus new transmission capacity that is installed as the simulation progresses. The supply module includes all existing generation, near-term planned generating units, and new generation as dictated by the model. Supply is determined first by load balancing—enough power must always be generated to meet projected load—but then it is constrained by transmission capacity, resource availability, reserve constraints, and clean energy policies. When adding renewable energy resources to the grid, ReEDS relies on a detailed characterization of many technologies. For solar energy, it considers utility-scale and distributed photovoltaics (PV) and concentrated solar power (CSP). Modeling these resources includes forecasting technology improvements and estimating interconnection and operation costs. ReEDS performs unit commit and economic dispatch when simulating the power grid.

## IV. RELIABILITY

Scaling solar (and wind) deployment up to over a terawatt of capacity over the ensuing decades will make the grid much more reliant on VRE inverter-based resources (IBRs). A large share of PV and storage will be installed at residential and commercial sites, entailing that a significant amount of generation shifts toward being distributed. The challenge will be to ensure reliability as this newly fashioned grid evolves.

One aspect of reliability is resource adequacy (RA), the ability of the grid to meet demand at any given time. There must be enough capacity in generation, transmission and distribution lines, and other electrical equipment to keep the lights on. Increased reliance on variable resources necessitates accurate weather forecasting. The SFS uses weather data from 2007-13 to simulate a variety of operating conditions and estimate capacity credit, the fraction of nameplate capacity actually available at a given time. It also explores scenarios with increased extreme weather events that may arise due to climate change. Energy storage plays a significant role in meeting RA, but we will delve into that later. The SFS finds that PV proliferation will narrow the daily peak electricity demand. Flexible demand—such as demand response programs—is one way to redistribute this peak over a few hours, thus reducing the peak. This plays an important role in the *Decarb + E* scenario. Upgrading the transmission grid is another tactic for improving RA. The SFS finds that depending on the scenario, transmission capacity expands by 7 to 39% by 2035, as transmission can provide capacity across regions that have staggered demand peaks. Distribution also needs to increase, but this is not directly modeled by ReEDS.

In terms of operational reliability, IBRs are not necessarily less reliable than traditional synchronous generators, but they do have *different* challenges. Operational reliability is concerned with maintaining grid voltage frequency at 60±0.05 Hz and voltage levels close to 1 per-unit. This can be a challenge during contingency events where transmission lines or large amounts of generation suddenly go offline. When a contingency event occurs, the physics of synchronous generators provides an automatic inertial response, where the kinetic energy stored in the spinning mass is converted to electrical power, and the generator begins to slow down. This happens over a few seconds, allowing time for contingency reserve generators to spin up. IBRs do not have this inertial response, so they must rely on digital instruments to measure the rate of change of frequency and increase output, if operating below 100%. This response is called the fast-frequency response. Synchronous generators also can inject high current when a fault occurs, while IBRs cannot. This necessitates different overcurrent protection schemes and additional high fault current inverters.

## V. VARIABILITY

As mentioned before, a key challenge accompanying the solar penetration predicted by the SFS is the variability of the solar resource. In other words, there must be a mechanism to compensate for the diurnal aspect of solar generation causing what will be 45% of the grid's generating capacity to be unavailable outside of daytime hours. This is not felt immediately, as initial solar penetration has a high capacity credit, meaning it can readily meet high daytime demand. As the penetration of solar generation increases, the peaks of net demand not met by solar will shift away from hot summer days to later in the day, or in the case of increased electrification of heating loads, to winter months where solar generation is diminished. The challenge will be amplified as the existing peaking capacity retires from age and to meet carbon reduction requirements. Given the emissions goals set out in the *Decarb* and *Decarb + E* scenarios, we will need to find an alternative strategy of meeting peak loads without reinvesting into fossil fuel based peaking plants.

The SFS predicts one resolution to this dilemma will be a significant increase in the use of storage technologies but not immediately, as seen in figure 2. While storage capacity increases in all three scenarios, the rate of increased capacity remains under 5 GW/year until 2026. Before this point, increased storage must compete commercially with existing generation capacity of which there is a surplus currently in the United States. Once current peaking capacity retires, storage technology continues to mature, and solar generation capacity has increased significantly, storage capacity growth will sharply escalate. The SFS reports that there will be a synergy between solar and storage which can overproduce during sunlight hours and redistribute that to the shifted net load peaks occurring beyond solar generation's direct reach aided by its ability to discharge quickly to match the steep ramp up created by high solar penetration. The SFS also reports that initial storage capacity will be focused on shorter duration storage (<4 hours) transitioning to longer storage in the 2040s as the typical peaks have shifted and widen due to prior storage development and peak shift away from the summer to the winter where peaks last for longer. In total, the SFS predicts storage capacity will reach over 800 GW by 2050 in the *Decarb* scenario and double that amount in the *Decarb + E* scenario. Given that the current capacity of all storage technologies (pumped hydro storage and batteries) is about 25 GW, this increase will be a fundamental shift in the way peaking loads are met.

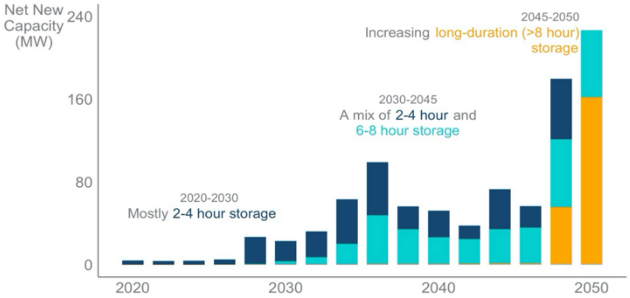

*Figure 2 (from [4]). Increases in energy storage for different durations in the Decarb scenario.*

## VI. CONCLUSION

The Solar Futures study is an excellent guiding document that allows us to focus future investment and efforts and know the scale of change that is required. The SFS also allows us to anticipate challenges such as the reliability of the grid and the variability of the solar resource and address them before they are fundamentally built into the U.S. power system. The modeling available for this study is crucial to providing these insights and is invaluable to making informed decisions. The SFS and its proceeding incarnations (SunShot Vision Study and On the Path to SunShot) allow us to track our progress as we make the necessary transition of decarbonizing out electric grid and cultivating solar power's key role in that transition.

# REFERENCES

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