Does How we Decarbonize Matter? An Examination of the Potential Energy Poverty Impacts of Fossil Asset Replacements

BY AMANDA J. HARKER STEELE,[a] CHRISTOPHER NICHOLS,[b] AND GAVIN PICKENPAUGH[c]

ABSTRACT

Replacing fossil assets with low-carbon alternatives will influence the costs associated with maintaining a competent, reliable grid (i.e., total systems costs). Noting over time any resulting system cost increases will likely be borne by consumers, this paper aims to provide insight into the potential energy poverty impacts that may result.

1. INTRODUCTION

Energy systems are evolving in response to changing energy market and policy conditions. Perhaps the most notable of which are the goals set forth to achieve carbon pollution free electricity by 2035 and economy-wide net-zero emissions by 2050 (Fam & Fam, 2024; The White House, 2021; 2021). Different pathways have been prescribed to meet these stated targets, most of which have suggested replacing legacy fossil-based power generation assets (LFAs) with low-carbon alternatives (LCAs) (e.g., wind or solar photovoltaics [PV] paired with battery storage or advanced fossil-based assets equipped with carbon capture and storage [CCS]) (The White House, 2021; Williams, et al., 2020; Bistline, et al., 2023; IAE, 2023). As the grid mix changes, however, so too will the costs associated with maintaining its reliability, otherwise known as the total systems cost (TSC) (Bartlett, 2019; Byrom, et al., 2021).[1]

Replacements that lead to higher TSC can adversely impact households who are already energy burdened (i.e., spending more than 6% of their gross income on energy costs) (DOE Office of State and Community Energy Programs, 2024). As the costs associated with replacing generation assets will over time, either directly or indirectly, be financed by consumers including residential customers, who could end up paying a higher price per-unit of consumption, as a result (Byrom, et al., 2021; Davis & Hausman, 2021; Wood, et al., 2016).[2] Noting whether a household is energy poor (i.e., living in a state of energy poverty) is directly influenced by whether they are energy burdened, which depends on the price they pay to consume electricity, this paper aims to provide insight into the influence different LCAs could have on household energy burdens.

The potential effect of each competing LCA is inferred from further analysis of results produced by the National Energy Technology Laboratory's (NETL) System Cost of Replacement Energy (SCoRE) tool having been applied to the Electric Reliability Council of Texas (ERCOT) operating region (Harker Steele, Sharma, Pena Cabra, Clahane, & Iyengar, 2022). NETL's SCoRE tool provides estimates of the potential change to an operating region's TSC if its LFAs were to be replaced with competing LCAs. The replacement is assumed to occur in response to a need to achieve a percentage wise reduction in carbon dioxide (CO_2) emissions across the region (i.e., meet a decarbonization target) and each LCA is individually considered by the tool (i.e., assumed to be the only technology option available to replace the LFAs).

The SCoRE tool presents results for each competing LCA considered on a per-megawatt hour (MWh) basis, under the assurance that sufficient generation is available to meet hourly demand (i.e., zero loss of load events occur) (Harker Steele, Sharma, Pena Cabra, Clahane, & Iyengar, 2022). In this sense, results represent the average cost to the consumer from deploying the LCA considered (and any necessary additional grid services) in place of the region's LFAs (Byrom, et al., 2021; Greenstone & Nath, 2019).[3] All else equal, assuming a simplistic, vertically integrated environment where utilities are responsible for both power capacity and retail provision in the region, results represent first-best[4] estimates of the potential change in the retail price of electricity (i.e., retail rate) that may result from the replacement.

Understanding how retail rates could change in response to each LCA being deployed allows us to identify LCAs that could have progressive (i.e., decrease retail rates), regressive (i.e., increase retail rates), or proportionate (i.e., do not change retail rates) impacts on household energy burdens. Providing some insight into the distributional equity impacts of decarbonizing electric grids via the replacement of LFAs (Zachmann, Fredricksson, & Claeys, 2018). Although our results are based on a simplified model of the decision-making processes that occur within and across an operating region's grid to meet load, they do illustrate how replacing LFAs with different LCAs might affect people who are experiencing or nearing the experience of energy poverty, as requested of papers for this special issue of Energy Forum.

2. SYSTEM COST OF REPLACEMENT ENERGY (SCoRE) TOOL

The SCoRE tool can be implemented in any operating region so long as the data necessary to operate the

[a] Corresponding Author. National Energy Technology Laboratory, Research Economist, 3610 Collins Ferry Road, Morgantown, West Virginia 26505, United States, Amanda.HarkerSteele@netl.doe.gov
[b] National Energy Technology Laboratory, Physical Scientist, 3610 Collins Ferry Road, Morgantown, West Virginia 26505, United States, Christopher.Nichols@netl.doe.gov
[c] National Energy Technology Laboratory, Economist, 626 Cochran Mill Road, Pittsburgh, Pennsylvania, 15236, United States, Gavin.Pickenpaugh@netl.doe.gov

tool are available for the region. Data include hourly generation and load (L) served by each legacy asset (fossil and non-fossil based) during analysis year, ; the cost to install, operate, and maintain each generation asset (i.e., the capital and O&M costs); the fuel costs to operate each asset; the costs associated with integrating a new asset into the grid; and if applicable, the CO_2 emissions produced by each LFA in year *t* (Harker Steele, Sharma, Pena Cabra, Clahane, & Iyengar, 2022). Once data is obtained, the SCoRE tool executes a scenario run by first identifying the LFAs within the operating region of interest, the capacity each supplied to the grid in year *t* and the CO_2 emissions they produce per annum.

The SCoRE tool then systematically steps through the replacement of capacity supplied by the region's LFAs with the candidate LCA under consideration. The tool replaces the LFA with the highest carbon footprint first, followed by LFAs that emit relatively fewer CO_2 emissions. Capacity is replaced on a one-to-one basis unless built-in checks within the SCoRE tool reveal there is insufficient generation available to meet L as a result. If this is the case, then generation from remaining firm low carbon intensive assets (FLCIAs) (e.g., natural gas combined cycle [NGCC] units) is used to make up any deficit. If any deficit is unable to be met using the remaining FLCIAs then the tool estimates the maximum legacy, fossil asset capacity (MAXFC) replaceable without the occurrence of a loss of load event (LOLE). [5]

After balancing, at each discrete addition of capacity from the candidate LCA considered (or similarly, removal of incremental capacity supplied by the LFAs) the SCoRE tool computes the resulting decrease in CO_2 emissions—decarbonization target achieved—and the SCoRE metric for the LCA corresponding to that target. The SCoRE metric is calculated following equation (1),

$$SCoRE_{ji} = \frac{TSC_j - TSC_i}{EG_j} \qquad (1)$$

where TSC_j represents the TSC when a candidate LCA, *j* has been brought online to replace the LFAs, *i*; TSC_i represents the TSC under the baseline, business-as-usual (BAU), non-replacement, and *EG* is the electricity generation, measured in megawatt-hours (MWh). The TSC under both the replacement and BAU scenario are defined as the sum of the capital, fixed and variable operations and maintenance (O&M) costs, fuel costs, and interconnection costs.[6]

3. SETTING THE STAGE—DATA

Results from an application of the SCoRE tool to the ERCOT's 2019 grid mix are presented in Figure 1—see also Harker Steele et al. (2022).[7] Each point along a curve represents the resulting change in the TSC following the replacement of capacity supplied by the ERCOT's LFAs, which include coal and natural gas-fired generation assets, with the corresponding LCA. The LCAs we consider include coal with CCS, natural gas (NG) with CCS, wind plus lithium-ion (Li ion) battery storage, solar plus Li ion storage, and solar plus flow battery storage.

To compute electricity prices for residential customers in the ERCOT in 2019 we relied on data reported on EIA Form-861, a mandatory census of retail electricity sales by utility industry participants (EIA, 2024; Greenstone & Nath, 2019). The average revenue per MWh of electricity sold to Texas residential customers in 2019, weighted by the number of residential customers each utility provided electricity to together serve as a proxy for the retail rate paid by residential customers per-unit of electricity consumed ($/MWh).[8] Data reported by municipal, cooperative, and investor owned ERCOT utilities suggest the weighted average residential retail price of electricity in 2019 in the ERCOT was approximately $107/MWh.

4. CONSIDERATIONS FOR HOUSEHOLD ENERGY POVERTY VIA POTENTIAL IMPACTS TO HOUSEHOLD ENERGY BURDENS

Households who live in a state of energy poverty are unable to maintain adequate access to essential energy services, like electricity and heating, due to financial constraints (Faiella & Lavecchia, 2019; Cong, Nock, Qiu, & Xing, 2022; Reiner, Figueroa, Bates, & Reames, 2024). The consequences of energy poverty can in some cases be quite severe. For example, some households may forgo purchasing medication or seeking medical care in order to pay their home energy bills. A household's energy burden (i.e., percentage of gross income spent on energy/fuel costs) is the primary economic metric used to identify energy poor households in the United States (Bednar & Reames, 2020).

The U.S. Department of Energy's Low-Income Energy Affordability (LEAD) tool suggests Texas households, on average, spend 5% of their gross income on energy costs, indicating, the average Texas household is not yet but close to being energy burdened (DOE, 2024).[9] [10]To provide some insight into how each LCA considered might impact household energy burdens and thus energy poverty, we estimate the rate at which the calculated average retail price of electricity for residential customers serviced in the ERCOT in 2019 could change as result of each LCA (and any necessary FLCIAs) being

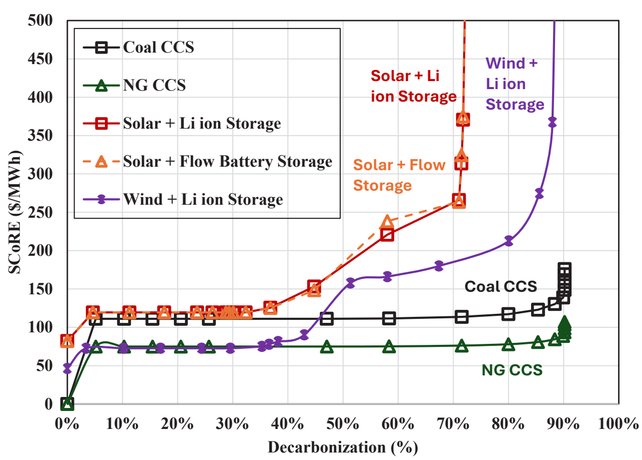

Figure 1. Results for the SCoRE values for replacements of legacy fossil assets with different new, low carbon assets

deployed in place of the region's LFAs within ranges of decarbonization targets achievable.

Assuming ERCOT based households do not adjust their electricity consumption and their gross income remains constant, the rate at which the average residential retail price of electricity is projected to change in response to a specific LCA being deployed in place of the region's LFAs is proportional to the change in the average household's energy burden we could expect. We calculate the projected rate of change in the residential retail electricity price in year *t*, $\%\Delta\, RRP_{p,t}$ following equation 2,

$$\%\Delta\, RRP_{p,t} = \left(\frac{[SCoRE_{i,j} + RRP_{A,t}] - RRP_{A,t}}{RRP_{A,t}}\right) \times 100 \qquad (2)$$

where $RRP_{A,t}$ is the calculated weighted average residential retail price of electricity in year *t*, which, recall for the ERCOT in 2019 was $107/MWh. All other terms in equation 2 are as defined previously. Applying equation 2 to the values presented in Figure 1 generates the results presented in Figure 2.

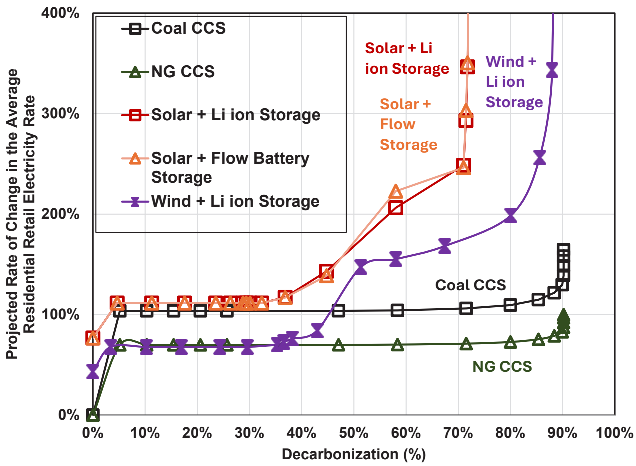

Figure 2. Projected rate of change in the residential retail electricity rate based on the SCoRE model results for each LCA

Given the operating characteristics of the LCAs vary, the decarbonization target they are able to achieve for having replaced a given amount of capacity from the region's LFAs varies. As such, how each LCA compares in terms of its potential influence on residential retail electricity rates at *a specific decarbonization target* (e.g., a 30% reduction in CO_2 emissions) is not able to be determined. Instead, LCAs can be compared in terms of their potential influence on residential retail electricity rates and corresponding household energy burdens, within set ranges of CO_2 emissions mitigation potential (a 25% to 50% reduction in CO_2 emissions). For the purpose of providing insight into how each LCA considered might influence household energy burdens we zoom in on four ranges of decarbonization potential—0% to 25% CO_2 emissions abated, 25% to 50% CO_2 emissions abated, 50% to 75% CO_2 emissions abated, and 75% to 100% CO_2 emissions abated—see Figure 3 through Figure 6 below.

Overall, our results suggest for decarbonization targets between 0 to 25%, using solar plus either Li ion or flow battery storage or coal with CCS in place of the region's LFAs could lead to more than a 100% increase in the presumed average retail price of electricity for ERCOT's residential customers in 2019. Replacing the region's LFAs with wind plus Li ion storage or NG with CCS leads to approximately a 70% increase in the presumed average retail price of electricity within the same range. Compared to NG with CCS, wind plus Li ion battery storage begins to lead to more significant increases in the presumed average retail price of electricity between 40% to 60% of CO_2 emissions being abated. Solar with either type of storage is not able to

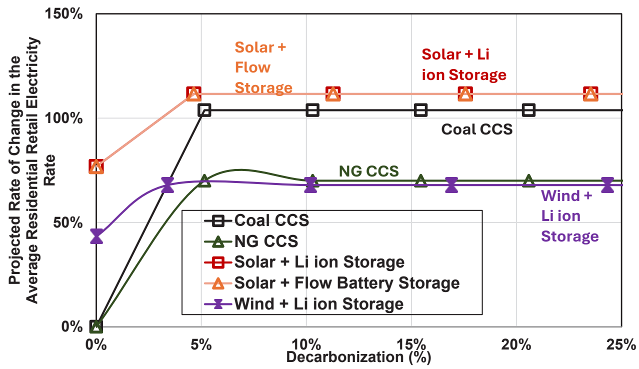

Figure 3. Projected rate of change in the residential retail electricity rate based on the SCoRE model results for each LCA between 0% to 25% CO_2 emissions abated

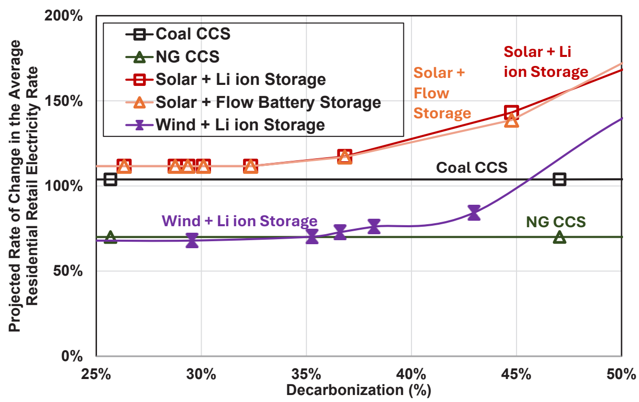

Figure 4. Projected rate of change in the residential retail electricity rate based on the SCoRE model results for each LCA between 25% to 50% CO_2 emissions abated

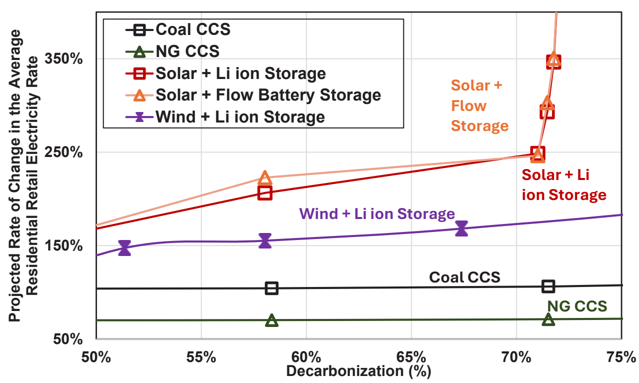

Figure 5. Projected rate of change in the residential retail electricity rate based on the SCoRE model results for each LCA between 50% to 75% CO_2 emissions abated

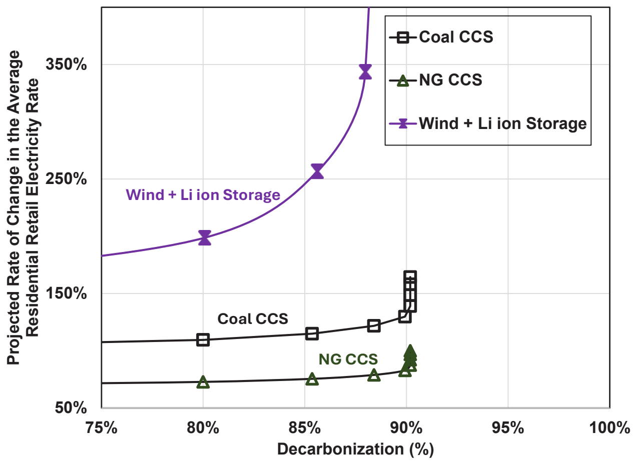

Figure 6. Projected rate of change in the residential retail electricity rate based on the SCoRE model results for each LCA between 75% to 100% CO_2 emissions abated

result in more than a 75% reduction in CO_2 emissions for the region without the rate at which it impacts the presumed average retail price of electricity increasing exponentially.

The rate at which coal with CCS and NG with CCS impact the presumed average retail price of electricity for residential customers in region remains relatively constant (somewhere between a 70 to 75% increase in the presumed average retail price of electricity for residential customers if NG with CCS is the LCA deployed; between a 100% to 110% increase in the presumed average retail price of electricity for residential customers if coal with CCS is the LCA deployed) until more than 80% of the region's CO_2 emissions are abated. None of the LCAs considered were found to be technically capable of sequestering 100% of ERCOTs CO_2 emissions in 2019.[11] As such, we are unable to provide a range of the potential impact each LCA considered could have on the presumed average retail price of electricity for residential customers in ERCOT under a zero-emissions future.

As suggested earlier, under the assumption that ERCOT-based households do not adjust their electricity consumption and their gross income remains constant, the results above suggest all else equal, achieving between a 0 to 25% reduction in the region's CO_2 emissions using solar plus storage or coal with CCS could lead to more than a 100% increase in their energy burden. For example, if households had an energy burden equal to 6%, then they could face an energy burden of 12% if solar plus storage or coal with CCS were used to replace the ERCOT's LFAs to achieve a 25% reduction in emissions. Doing so using wind plus Li ion storage or NG with CCS could lead to approximately a 70% increase in the household's energy burden (e.g., if households had an energy burden equal to 6% they would face an energy burden of 10.2% as a result).

The rate at which the presumed average retail price of electricity is estimated to change in response to a 25% to 50% reduction in CO_2 emissions being achieved is smallest if NG with CCS or wind plus Li ion battery storage are used to replace the region's LFAs. Both are projected to increase the presumed retail rate of electricity by about 70% until around 40% of CO_2 emissions are mitigated. At which point, wind plus Li ion battery storage is projected to lead to about an 85% increase in the presumed price. In terms of the possible impact on household energy burdens—up until about 40% of CO_2 emissions are mitigated, NG with CCS or wind plus Li ion storage cold lead to a 70% increase in the energy burden of ERCOT based households (e.g., households who had an energy burden equal to 6% would face an energy burden of 10.2% as a result). Once 40% of emissions have been mitigated, we project household energy burdens in ERCOT could increase by about 85% if wind plus Li Ion storage is used (e.g., households who had an energy burden equal to 6% would face an energy burden of 11.1% as a result).

Lastly, coal and NG with CCS are identified as having the smallest potential impact on the presumed average retail price of electricity and thus household energy burdens when between 50% and 75% of CO_2 emissions are mitigated in the region. NG with CCS outperforms coal with CCS in terms of its projected impact. Relationships hold until about 80% of CO_2 emissions are mitigated for region. At which point, coal with CCS is projected to lead to a 110% increase in the presumed average retail price of electricity and thus household energy burdens (i.e., households who had an energy burden equal to 6% would face an energy burden of 12.6 % as a result); NG with CCS is projected to lead to about a 75% increase in the presumed average retail price of electricity and thus household energy burdens (i.e., households who had an energy burden equal to 6% would face an energy burden of 10.5 % as a result), all else equal.

It is suggested that households who spend more than 6% of their gross income on energy expenses are energy burdened (Drehobl, Ross, & Ayala, 2020). Given whether a household is or is not energy burdened is the primary qualifier used to assess whether it is living in a state of energy poverty, it is important to consider how changes in the way we produce energy, in particular electricity, to achieve stated decarbonization targets could impact residential consumers. While the results above are based on some very broad assumptions and back of the envelope calculations, they begin to uncover how replacing a region's LFAs with a specific LCA might lead to higher home energy burdens and how the impact of each LCA on household energy burdens could change depending on the percent of CO_2 emissions needed to be mitigated. This highlights the importance of considering not only the technical efficiency of using LCAs in place of LFAs but also the distributional equity impacts associated with doing so.

5. LIMITATIONS & NEXT STEPS

It is important to note the results above are based on the first-iteration of NETL's SCoRE tool having been applied to 2019 data for the ERCOT operating region—for more information see Harker Steele et al. (2022). As such, they do not represent values produced by the most recent version of the tool, which considers the time it takes to construct each LCA separate from the time it operates and needs maintained, allowing for the change in the TSC to be distributed over several years. Second, results are based on a simplified version of how changes in the TSC occur and are passed along to consumers. While an increase in TSC may not directly transcribe to an increase in the rate customers pay per unit of consumption, there is a strong relationship between the two since both regulated and non-regulated utilities will eventually pass along the costs of construction and operation of their generating units, and any backup required for reliability onto consumers in some form. Next steps for this work include evaluating all of the cost components that are used to build out the SCoRE metrics produced by the most recent version of the tool, as the estimated change in the system costs must fully capture the associated costs to assess results at select decarbonization targets. We also plan to investigate household energy burdens more fully within the operating regions where the tool is applied so we can more robustly identify the potential influence of each LCA on household energy burdens.

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Footnotes

[1] See Section for a complete definition of and a summary of the costs that make up the TSC.

[2] In the United States, privately held, municipally-run, and government owned utilities operate as natural monopolies, recovering their fixed cost of production by charging their customers higher fees overtime (Davis & Hausman, 2021).

[3] Examples of additional grid services include battery storage, increased monitoring, and transmission upgrades.

[4] A first-best estimate refers to an initial calculation or approximation of a value.

[5] See Figure 7 in the Appendix for a depiction of the mechanics of each replacement scenario run executed by the SCoRE tool.

[6] Interconnection costs refer to all of the costs incurred by an electric utility associated with connecting, switching, metering, and monitoring a physical asset along the grid system (Harker Steele, Sharma, Pena Cabra, Clahane, & Iyengar, 2022).

[7] ERCOT is tasked with supplying electricity to more than 26 million customers across the state of Texas, serving nearly 90% of the state's population (Electric Reliability Council of Texas, 2022). ERCOT also operates one of the nine North American independent system operators (ISOs) and more uniquely as its own physical interconnection and balancing authority (Electric Reliability Council of Texas, 2022; EIA, 2016).

[8] This assumes retail customers pay the same cost per-unit of electricity consumed regardless of their income level, other incentive structures or programs they engage in with their electricity provided (e.g., demand response).

[9] The LEAD tool suggests Texas households who heat their homes using electricity spend about 2% of their gross income on energy costs.

[10] Households who spend more than 6% of their income on energy costs are considered energy burdened (Drehobl, Ross, & Ayala, 2020).

[11] The carbon capture systems modeled within the SCoRE tool had an assumed capture rate of 90%.

APPENDIX

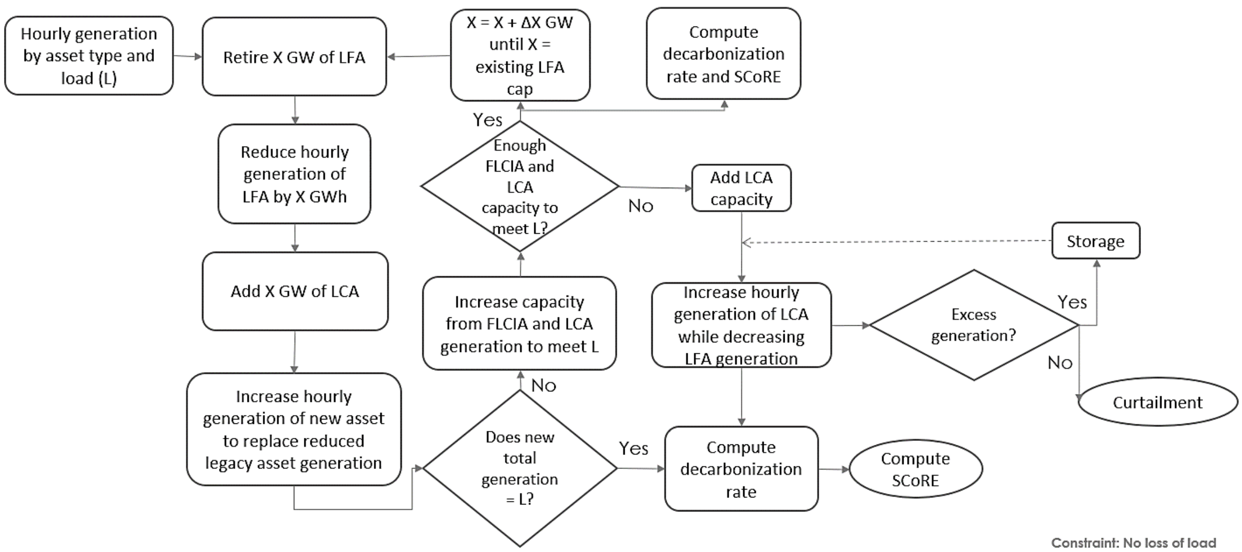

Figure 7. Mechanics of a Typical Replacement Scenario Modeled within the SCoRE tool