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Understanding the role and design space of demand sinks in low-carbon power systems

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ABSTRACT

As the availability of weather-dependent, zero marginal cost resources such as wind and solar power increases, a variety of flexible electricity loads, or ‘demand sinks’, could be deployed to use intermittently available low-cost electricity to produce valuable outputs. This study provides a general framework to evaluate any potential demand sink technology and understand its viability to be deployed cost-effectively in low-carbon power systems. We use an electricity system optimization model to assess 98 discrete combinations of capital costs and output values that collectively span the range of feasible characteristics of potential demand sink technologies. We find that candidates like hydrogen electrolysis, direct air capture, and flexible electric heating can all achieve significant installed capacity (>10% of system peak load) if lower capital costs are reached in the future. Demand sink technologies significantly increase installed wind and solar capacity while not significantly affecting battery storage, firm generating capacity, or the average cost of electricity.

1. Introduction

The widespread deployment of weather-dependent variable renewable energy resources, principally wind power and solar photovoltaics, can provide abundant, low-cost electricity intermittently [1]. Several classes of technologies or resources are likely to emerge to take advantage of this low-cost but variable electricity supply. Li-ion battery storage systems are cost-effective at relatively high utilization rates and best suited for several hours of discharge duration on diurnal cycles [2]. A variety of long-duration energy storage (LDES) technologies are in development and have the potential to provide significant flexibility to the grid over multi-day periods, but significant technological advancement is necessary for this class of storage technologies to be cost-effective [3]. Interruptible demands may curtail consumption during a handful of very high price periods when electricity supply is scarce, while time-shiftable demands, such as EV charging and heating, may regularly arbitrage the availability of low-cost electricity by moving consumption, typically over a span of hours, to align with these periods [4].

An additional class of electricity loads may be willing to consume exclusively during lower-price periods, flexibly harnessing intermittently available, low-cost, low-carbon electricity to produce some useful or valuable output product. We call these resources ‘demand sinks,’ a broad class of resources that encompasses a wide range of potential technologies that meet the following general requirements:

1. The technology must be technically flexible, allowing it to respond effectively to low electricity prices
2. The output product must have a market value
3. The technology must be energy intensive (e.g., energy costs represent a major share of costs, such that operating around the availability of low-cost power is economically sensible)
4. Flexible operations must be highly automated such that significant costs are not incurred for idled labor during periods of low or zero output
5. The output product must be flexibly consumable and/or easily storable so that production may be interrupted when electricity prices are not affordable.

Some of the most frequently discussed potential demand sink technologies are (1) Hydrogen electrolysis [5,6], (2) CO_2 Direct Air Capture (DAC) [7], (3) Flexible resistive heating [8] for industrial process heat or district heating, possibly in conjunction with traditional gas-fired boilers [9], (4) Bitcoin or other cryptocurrency mining [10], and (5)

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Desalination of water [11,12].

We note that class of 'demand sink' resources includes some sector-coupling technologies, which integrate production or consumption across multiple energy carriers [13,14], and power-to-x technologies, which consume electricity to produce heat or fuels [15–19], which have been analyzed in previous literature focused on e.g., their impact on the environment [20], utilization of renewable energy [18], transmission reinforcement [21], cost of energy transition [13], and future energy mix [22]. Recent studies have also examined the individual technologies' flexibilities and constraints in response to market dynamics and their consequential impacts on the aforementioned factors [21,23–25]. However, the general class of demand sink technologies encompasses a wider range of processes that convert intermittently available low-cost electricity to valuable outputs other than fuels or heat, and the category is not coterminous with all sector-coupling or power-to-x technologies (which may also fall into other demand categories, such as firm, interruptible or time-shiftable demands, see Appendix C [51–53] and Figure C.9).

This study provides a general framework to evaluate any potential demand sink technology and understand what characteristics make a candidate technology viable for large-scale, cost-effective deployment in low-carbon power systems. At the same time, this paper illustrates how the demand sinks operate in the grid and demonstrates how their deployment affects other resources and technologies in the power system in ways that are distinct from other classes of flexible electricity demand.

The rest of the paper is organized in the following way. Section 2 describes the experimental setup of the study that establishes a design space to evaluate any demand sink technology. Section 3 showcases the results from the experimental setup and describes the design space under increasingly stringent carbon dioxide emission limits and two characteristically different systems, Northern and Southern. Section 4 showcases the location of various demand sink technologies in the design space and evaluates their viability in a real-world system, and Section 5 provides details of the methodology and lists limitations.

2. Experimental setup

To evaluate the general class of demand sink technologies, this study employs the state-of-the-art electricity system capacity expansion optimization model, GenX, with high temporal resolution (8760 hours) and detailed operating decisions and constraints using a cost-minimizing objective [26]. We employ GenX to model a 'greenfield' expansion plan (e.g. considering no existing installed capacity) for a generic power system with the candidate resource options listed in Appendix Table D.2. We vary the conditions in this generic system (technology costs, demand profiles, etc.) exogenously to reflect a range of possible real-world conditions in a stylized and tractable manner while avoiding the idiosyncratic nature of real-world systems in our experimental design [3,27,28].

This study represents a broad range of possible demand sink technologies generically by modeling variations in two key parameters: (1) the demand sink capital costs, defined in terms of U.S. Dollars per kilowatt of electricity input that the demand sink can consume ($\$/KW_{in}$); and (2) the output value, defined in terms of U.S. Dollars per MWh of input electricity consumed ($\$/MWh_{in}$). This latter term encompasses a combination of the value of the end product, less variable costs, and the cost of storage or transport to get the product to market, and accounts for the efficiency of conversion of input electricity to a product. We then model a wide range of combinations of these two key parameters that span the range of feasible characteristics for potential demand sink technologies. We collectively refer to the range of possible combinations of these two parameters as the demand sink 'technology design space', and we model a total of 98 discrete combinations of parameters. We can then evaluate existing technologies' performance within that space, as well as explore the value of currently infeasible regions that might be achievable by the year 2050 or before with sufficient research and development or novel technologies. We do not model these technologies individually; only a generic demand sink resource is evaluated in the modeling setup. The potential future feasible ranges for several known demand sink technologies, which include projected costs and market conditions, are based on various peer-reviewed studies and can be found in Table 3.

Furthermore, we evaluate the technology design space for demand sinks in multiple power system contexts encompassing different wind, solar, and demand characteristics. This includes a 3-zone system with weather and demand conditions typical of New England and a 3-zone system with weather and demand typical of Texas, referred to herein as the Northern and Southern systems, respectively. Note that these systems are not meant to represent the actual New England or Texas power systems but rather to provide test systems with diverse meteorological conditions. We model a demand profile with high electrification of transportation, space, and water heating energy demands by default, with additional analysis observing the effects of lower electrification. Additionally, we test the effect of increasingly stringent carbon dioxide emissions limits, corresponding roughly to a 90%, 95%, and 100% reduction in emissions. In total, we evaluate the full demand sink technology design space in 6 different main scenarios and 5 different sensitivity scenarios for a total of 869 distinct cases. See Section 5 for further detail on experimental design and assumptions.

Before evaluating the effect of demand sinks on various components of the power system, as well as their operations within that system, it is important to establish an understanding of the design space modeled in this study. The first key parameter is the demand sink capital cost or capex, measured in U.S. Dollars per kilowatt of electricity input consumed by the demand sink ($\$/KW_{in}$). It is based, across all scenarios, on a conversion from annuitized investment costs with a 20-year financial asset life, an after-tax weighted average cost of capital (WACC) of 7.1%, and a fixed operations & maintenance (FOM) cost of 4% of the capital cost. Appendix Table D.5 facilitates the use of our results to evaluate technologies with different financial asset life and/or WACC assumptions.

The second parameter, which will be on the horizontal axis of all design space plots in this study, represents the output value or average net revenue earned from the output produced for each 1 MWh of electricity consumed by the demand sink (denoted as $\$/MWh_{in}$) and is defined as per Eq. (1):

$$Value = (Price - T\&S)(Eff.) - VOM \tag{1}$$

where *Value* is the output value in \$ per MWh of electricity input consumed by the demand sink ($\$/MWh_{in}$), *Price* is the product market price per whatever unit the product is denominated in (\$/unit), *T&S* is the cost of transport and/or storage required to deliver the product to market (in \$/unit), *Eff.* is the conversion efficiency (in units of product output per MWh_{in}), and *VOM* is the variable operations and maintenance costs per MWh of electricity consumed ($\$/MWh_{in}$). Note that *VOM* represents only non-electricity related O&M costs, as the modeling accounts for input costs endogenously. Additionally, the *T&S* term is included here for completeness, as our modeling setup does not explicitly represent any transport and/or storage-related costs for products produced by demand sinks. This is further discussed in Sections 4 and 5.4.

This generic *Value* parameter thus combines and abstracts away any details associated with individual technologies, such as variable costs and efficiency. This simplification allows our parametric analysis to proceed in two dimensions, simplifying the search of the design space. To interpret this *Value* parameter, which ranges from \$20–\$100/MWh_{in} in this study, and convert it to physical output product prices (in whatever unit that product is typically measured), we then have to account for the specifics of a given technology and use the following equation:

$$Price = \frac{Value + VOM}{Eff.} + T\&S \tag{2}$$

3. Results

3.1. Installed demand sink capacity

We define a ‘significant’ installed demand sink capacity as 10% of the system’s peak hourly load, with the objective of providing an indicator of when one might reasonably consider the demand sink to be a significant part of the modeled power system. We allow a generic demand sink resource to be installed in each cost-optimized power system, and we record installed capacity levels across the various discrete design space assumptions modeled. Fig. 1 shows the installed demand sink capacity as a fraction of the system peak load in both the Northern and the Southern systems, subject to increasingly stringent carbon dioxide emissions limits.

The results in Fig. 1 allow us to understand under what capital cost and market conditions various technologies should be installed. Because of higher electricity prices in the Northern system, we observe that more favorable market conditions (a lower capital cost or a higher output product value) are needed to achieve the same demand sink penetration as in the Southern system. The increasing stringency of the emissions limit increases the average price of electricity as well, resulting in a similar requirement for slightly more favorable demand sink parameter conditions, but the effect is small. This is due to the fact that demand sinks consume power during lower price periods, which excludes hours when generators with high fuel consumption (and thus high CO_2 emissions rate) set the marginal price.

3.2. Demand sink impact on electricity prices

One way to quantify the impact of demand sinks on the power system is by considering the change in the average price of electricity. We define a ‘significant’ system cost reduction to correspond to a >10% decrease in the average price of electricity. Fig. 2 shows the results of modeling this impact.

We find that even in scenarios with substantial demand sink deployment, demand sinks generally do not significantly impact average electricity prices. In line with the results found for the installed capacity, the demand sink impact is relatively greater in the Southern system than in the Northern one. The stringency of the emissions limit has virtually no effect on the results. Demand sinks did not increase the average price of electricity in any of the scenarios considered.

Moreover, we find that while average costs do not change appreciably, the presence of demand sinks can alter the distribution of prices throughout the year. In particular, in scenarios with low capital cost demand sinks (<\$500/KW_{in}), electricity prices are more stable throughout the year, and periods of very low electricity prices become less frequent, as shown in Appendix Figure A.1. In higher demand sink

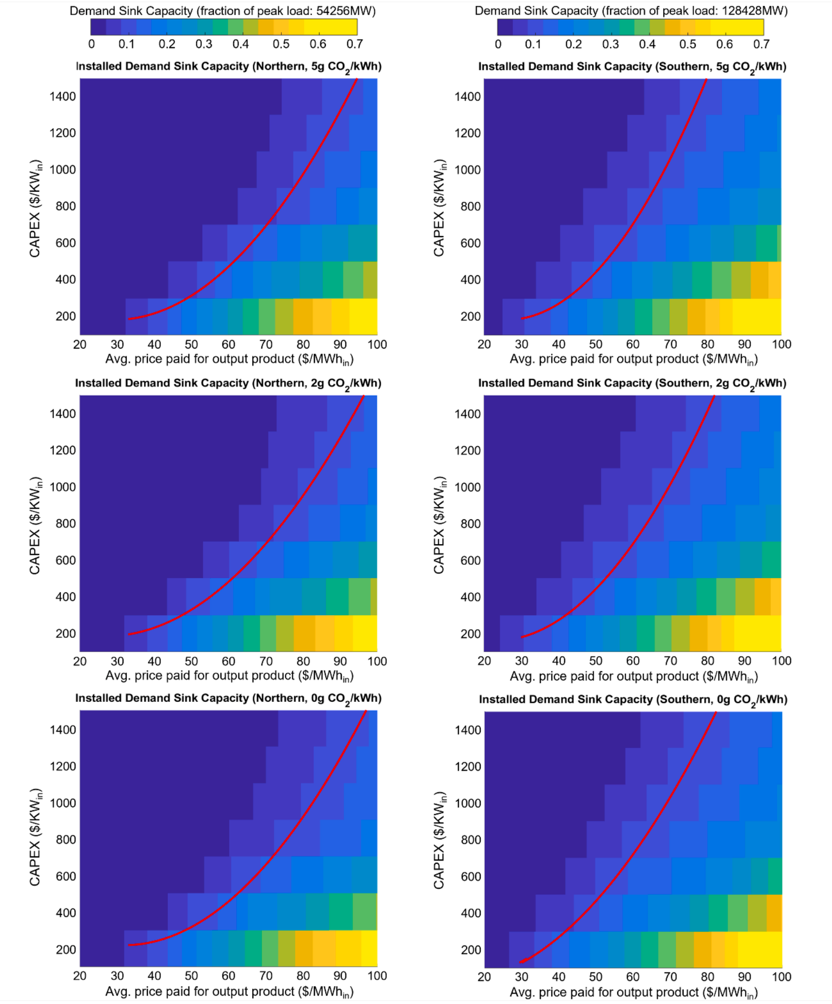

Fig. 1. Installed Demand Sink Capacity. Installed demand sink capacity in the system plotted as a fraction of the system’s peak load. The left column shows the results in the Northern system, and the right column shows the Southern system. From top to bottom, the stringency of the carbon dioxide emissions limit increases. The red line indicates the crossover to a ‘significant’ installed capacity (>10% of system peak load).

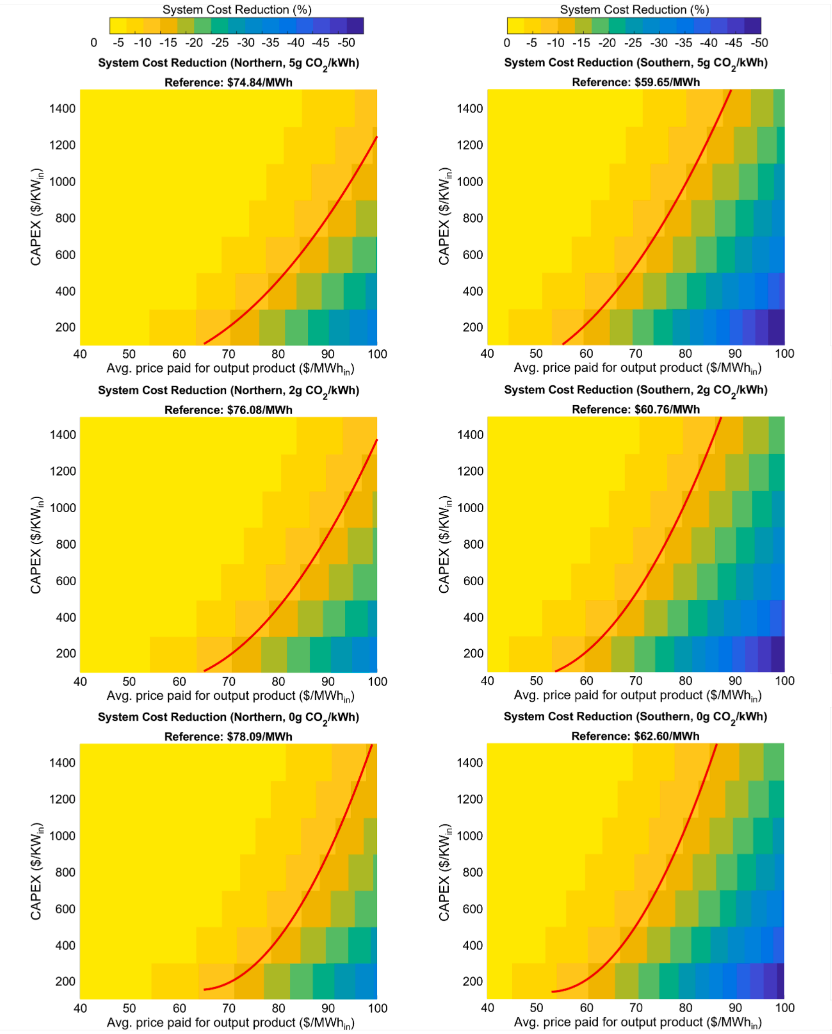

Fig. 2. Demand Sink Impact on System Cost. Change in system cost as compared to the reference scenario. The left column shows the results in the Northern system, and the right column shows the Southern system. The stringency of the carbon dioxide emissions limit increases from top to bottom. The red line indicates the crossover to a 'significant' cost reduction (>10%).

capex scenarios, we observe little change in the electricity price duration curves in the system. We also find that the average price of electricity used for demand sink production is about half of the average output product value in magnitude (44–56%, see Appendix Table B.2), with the difference representing the gross margin required to compensate the capital costs of the demand sink capacity. We also find that the average price of electricity consumed by demand sinks is 37–70% lower than the average price of electricity, reflecting the flexible consumption of electricity only when prices are favorable.

3.3. Demand sink impact on generator mix

Here we consider how demand sinks affect the installed capacities of the other available electricity resources. Fig. 3 presents the change in installed capacity of various resources as a function of demand sink capacity, including: (1) Solar, (2) Onshore and offshore wind ('Wind'), (3) Natural gas with Carbon Capture and Sequestration (CCS) and nuclear, as well as CCGT and OCGT plants in non-zero emission scenarios ('Firm'), and (4) Li-ion battery storage systems ('Battery Storage'). See Appendix Table B.1 for reference capacities in systems without any demand sink capacity.

Including demand sink technologies in the power system significantly increases renewable energy generating capacity to supply electricity for demand sink production. In the fully decarbonized power system, for every MW of demand sink capacity built, 0.95–1.15 MW of additional wind and solar capacity gets built in the Northern system and 1.0–1.9 MW of additional capacity in the Southern system. The relationship between installed demand sink capacity and the change in the capacity of the various resources can be found in Appendix Figure A.2. The main difference in results between the Northern and the Southern systems is that we observe very little to no additional wind capacity in the Northern system (Fig. 3). The LCOE of wind resources in the Northern system is significantly higher, which explains this difference. To compensate for this, we observe slightly higher increases in solar capacity in the Northern system.

The impact of demand sinks on the installed capacity of firm resources and battery storage systems is minimal. Across all scenarios, we observe a decrease in firm generating capacity of <4% of peak demand and an increase in battery storage system capacity of <6% of peak demand, as compared to the reference scenario. Even in cases where we observe significant installed demand sink capacity, we observe a decrease in firm capacity with a magnitude of only a small fraction of the demand sink capacity. This outcome is further explained in the section below and in Table 1.

3.4. Demand sink operations

Understanding how various demand sink technologies might

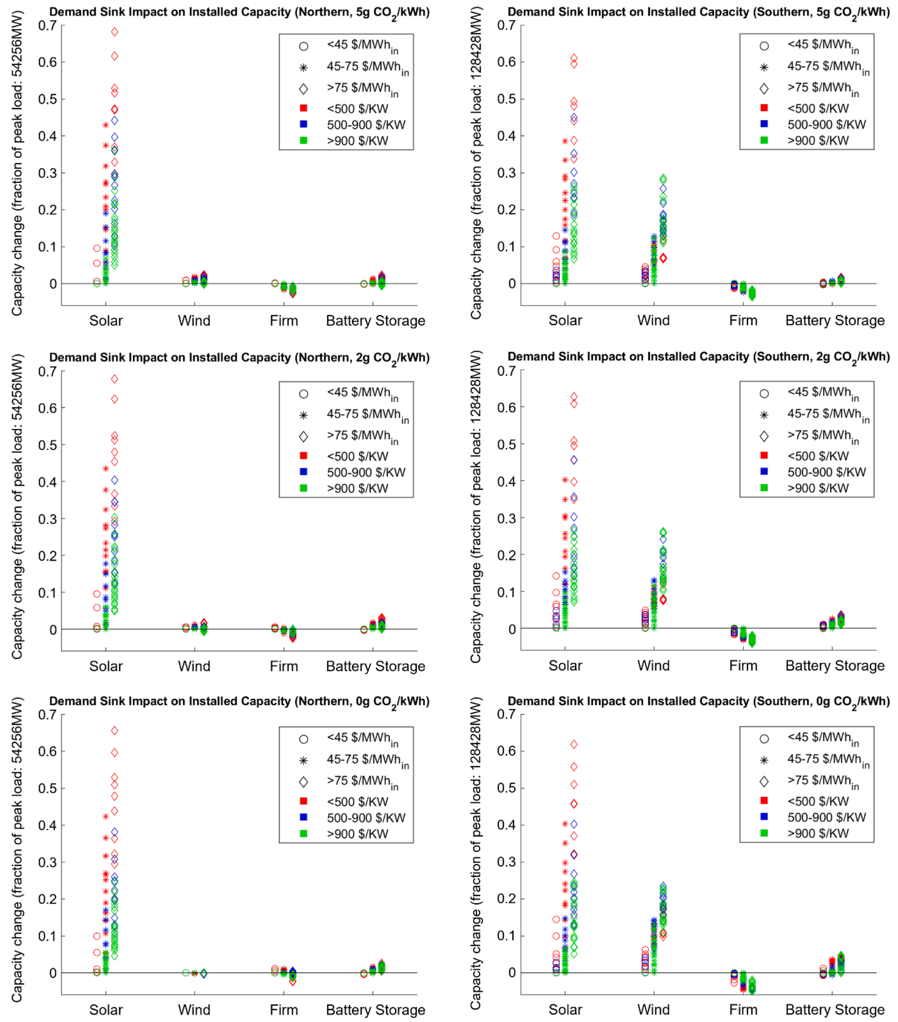

Fig. 3. Demand Sink Impact on Installed Capacity of Other Resources. Change in the installed capacity as a fraction of system peak load, as compared to the reference scenarios. The left column shows the results in the Northern system, and the right column shows the Southern system. The stringency of the carbon dioxide emissions limit increases from top to bottom. Results are grouped by both the demand sink output product value and the demand sink capital cost.

Table 1

Demand Sink Operational Results in Representative Scenarios. The scenarios in this table represent similar demand sink penetrations of around 10% of system peak load in both systems, respectively, across a range of demand sink capital cost assumptions. Changes in capacity are with respect to the reference scenario without demand sink technologies available. The additional renewable generation represents the generation by wind and solar resources installed in excess of reference capacity during the hour of peak net system load.

Scenario (0g CO$_2$/kWh)	Correlation Between Demand Sink Prod. and Net Load	Demand Sink Cap.(MW)	Change in Firm Cap.(MW)	Change in Battery Cap.(MW)	Change in VRE Cap.(MW)	Add'l Renewable Generation At Peak Net Load (MW)
Northern \$200/KW$_{in}$, \$42/MWh$_{in}$	− 0.79	5542	+610	− 153	+5387	0
\$800/KW$_{in}$, \$76/MWh$_{in}$	− 0.41	4978	− 334	+663	+4889	0
\$1200/KW$_{in}$, \$90/MWh$_{in}$	− 0.73	5651	− 279	+608	+5478	0
Southern \$200/KW$_{in}$, \$39/MWh$_{in}$	− 0.87	16,115	− 2352	+652	+18,376	1469
\$800/KW$_{in}$, \$68/MWh$_{in}$	− 0.58	14,423	− 2834	− 204	+25,253	4707
\$1200/KW$_{in}$, \$82/MWh$_{in}$	− 0.73	14,329	− 3077	+406	+25,929	2791

optimally operate within the power system is crucial, as it could have significant impacts on supporting infrastructure that might be needed to store output products, and it can possibly place restrictions on what technologies might qualify as a demand sink (which is further explored in Section 4). We first consider demand sink utilization rates. The demand sink capacity factor indicates what fraction of theoretical maximum production (if the demand sink was left on for the entire year) was achieved in a given scenario. This can then show what level of flexibility a demand sink technology might require, depending on where in the design space it operates.

The results can be found in Fig. 4, and they show a clear relationship between the demand sink capital cost and the utilization rate. Lower capex (<\$500/KW$_{in}$) demand sinks, a category in which technologies such as resistive heating or electrolysis might fall, ideally operate at a utilization rate of 30–40%, and thus exhibit a high degree of flexibility. This utilization level makes these technologies well-suited to use available wind and solar power with similar capacity factors. On the other hand, higher capex (>\$900/KW$_{in}$) demand sinks such as DAC ideally operate at a utilization rate of 75–95%. The underlying mechanism here is that higher capital costs require higher utilization rates to make a resource cost-effective. This result can help evaluate the level of flexibility required of certain technologies, adding a level of detail to what 'flexible' sinks might entail.

Across the various scenarios, we observe that demand sinks in the Northern system operate at a slightly higher utilization rate than in the Southern system. Moreover, the more stringent the emissions limit is, the higher the demand sink utilization is in any given scenario. These effects are directly related to the cost of electricity. A higher cost of electricity results in a higher utilization rate for demand sinks than in a scenario with a lower cost of electricity, generally. One might expect that given a fixed demand sink capacity, higher electricity prices would lead to lower demand sink utilization rates. However, in a long-run context, higher electricity prices lead to lower installed demand sink capacity. As a result, the smaller installed demand sink capacity is utilized at a higher rate, as what is built can take advantage of over-generation on the margin more frequently. The opposite occurs for lower electricity prices, leading to greater installed demand sink capacity with lower average utilization rates.

A full year of demand sink operations for certain representative scenarios can be found in Appendix Figure A.3. These images show the utilization results explained above from another point of view; high capital cost demand sinks operate at 100% of their capacity most of the time, whereas lower capital cost demand sinks operate much more intermittently and more frequently at part-load. The relationship between net system load and demand sink production across the year is represented in Appendix Figure A.4 and Table 1. At periods of high net load, we observe lower demand sink production. Since these periods would correspond to higher prices of electricity, this result is in line with expectations.

Additionally, Table 1 shows the displacement of firm generating capacity in those same representative scenarios. We pick the day with the highest net load in the system of the year, and we calculate what amount of electricity is generated by the additional renewable capacity induced by the presence of demand sinks during the highest net load. We observe, especially in the Southern system, that the displacement of firm generation capacity by demand sinks is closely related to this additional

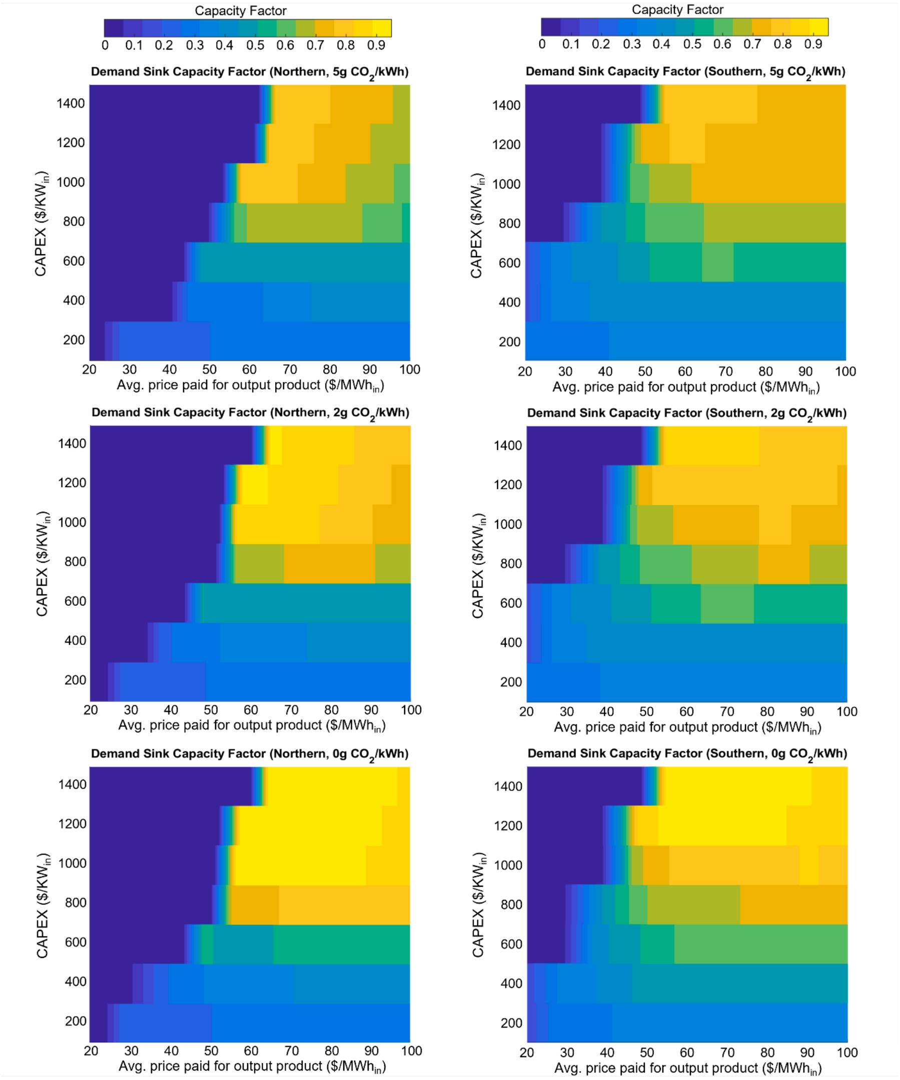

Fig. 4. Demand Sink Capacity Factors. The left column shows the results in the Northern system, and the right column shows the Southern system. The stringency of the carbon dioxide emissions limit increases from top to bottom.

renewable generation (relative to the reference case without demand sinks) during the peak net load hour, in combination with the change in Li-ion battery storage capacity. In the Southern system, we find that in the hour of highest net peak load, the additional renewable capacity operates between a 8–19% utilization rate, enabling a reduction in firm capacity of 2.3–3.1 GW, a magnitude equal to 15–21% of installed demand sink capacity. In the Northern system, we observe less displacement of firm capacity. The additional renewable generation during the net peak load hour is zero in the Northern system, as the hour is after daylight, and the scenarios did not result in additional wind capacity as compared to the reference scenario. Rather, we see that changes in Li-ion battery capacity operating at a 46–50% utilization during this period enable displacement of several hundred megawatts of firm capacity (equal to 5–7% of installed demand sink capacity).

Another way to understand the effect of demand sink operations on other generation sources in the power system is by considering the cycling of thermal plants. We measure the impact on thermal cycling by the change in thermal plant start-up costs throughout the year, of which the results are shown in Appendix Figure A.5. We find that demand sinks with capital costs <\$800/KW_{in} reduce thermal start-up costs by 5–50% as compared to the reference scenario. By consuming electricity during periods of high wind and solar output, demand sink operations increase the net load and can thus reduce requirements for thermal units to turn off, keeping thermal plants running for longer periods of time. Demand sinks with capital costs >\$800/KW_{in} can increase thermal start-up costs by 0–25%, where the highest increase is found in scenarios with the highest demand sink output product value. In these scenarios, demand sinks can actually be cost-effectively powered by firm generating resources at times, resulting in the increase in thermal cycling we observe.

3.4.1. *Demand sink impact on renewable curtailment*

Flexible loads are sometimes thought of as a potential solution to the curtailment of renewable electricity, where these technologies would simply soak up excess electricity that would otherwise be curtailed. By observing the curtailment of wind and solar generation across the demand sink design space, we observe that this is, in fact, only the case for demand sink technologies with low capital costs. We measure the curtailment as a fraction of the total theoretical renewable generation potential, which depends on the installed capacity, as a way to normalize curtailment across scenarios. As shown in Appendix Figure A.6, very low capital cost demand sinks (<\$400/KW_{in}), which operate most flexibly, can cause a significant reduction in curtailment (10%–75% less renewable curtailment than in the reference scenario). In all other demand sink capex scenarios, we observe a smaller change in curtailment, ranging from a 0–40% reduction in the Northern system, while we observe a 0–40% *increase* in the Southern system. This increase in curtailment only occurs with less stringent emissions limits and for very high output product value, where it is especially favorable to install additional generating capacity to power demand sinks, even if some of that additional renewable energy generation is wasted. However, in the fully decarbonized scenario, we typically observe close to zero change in curtailment in the Southern system for a demand sink capital cost >\$400/KW_{in}. Instead of simply using what would otherwise be wasted wind and solar output, the presence of cost-effective demand sinks results in the installation of *additional* renewable energy capacity (on a roughly 1:1 basis in the Northern system and greater than 1:1 basis in the Southern system) which primarily serves demand sinks. So rather than primarily functioning as a solution to curtailment of renewable capacity installed to meet typical electricity loads, demand sinks appear to be an opportunity to use *more* low-cost renewable energy on an intermittent basis to produce additional valuable outputs.

Alternatively, when considering *absolute* changes in the amount of electricity that is being curtailed, >\$400/KW_{in} capex demand sinks can increase total curtailment by up to 80% as compared to the reference scenario. While more electricity is curtailed in total, it is still a smaller fraction of the total theoretical generation because of the significant increases in renewable generating capacity. Since the higher capital cost demand sinks are less closely tied to renewable availability, but it is still favorable to build more renewable capacity, these demand sinks turn out to be less flexible in utilizing excess electricity.

3.5. *Sensitivity scenarios*

The main sensitivity analysis in this study is inherent to the comparison in results between the Northern and the Southern systems, in which we find that with higher renewable generation potential and lower average prices of electricity, demand sinks are more favorable in the Southern system. At the same demand sink capital cost and output product value, we will find higher installed capacity and total annual production in the Southern system than in the Northern system across all cases. In addition to that, we observe the effect of an increasingly stringent emissions limit, which effectively raises the average price of electricity and thus makes demand sinks less favorable. However, between the 90%, 95%, and 100% CO_2 emissions reductions modeled, the effects on demand sink results are minimal.

To further evaluate the robustness of this study's results, we apply a variety of additional scenarios to the case most sensitive to changes: The Northern system with a 0g CO_2/kWh emissions limit. Across five different sensitivity scenarios, this results in the modeling of 275 additional cases. The scenarios we test are as follows:

1. Low electrification of transportation, space, and water heating energy demands
2. Low wind and solar resource cost
3. Low wind, solar, and battery storage systems resource cost
4. Low firm resource cost (modeled through natural gas with CCS and nuclear)
5. Low price elasticity of demand for the demand sink output (demand falls to zero slower at higher prices)

All corresponding cost assumptions can be found in Appendix Table D.3, and the results are shown in Figure 5 and Appendix Figures A.7, and A.8.

First, we observe that the lower electrification scenario does not significantly impact demand sink capacity decisions or operations; total annual production stays roughly the same across all scenarios as compared to their base case counterpart. This indicates that the value of demand sinks is largely insensitive to changes in the pattern or volume of other electricity demands.

The three scenarios involving low resource costs all have a similar effect: They increase the total annual demand sink production. Since those scenarios effectively reduce the average cost of electricity, it becomes more favorable to use demand sinks at lower output product values. Low renewable resource costs increase the installed demand sink capacity across all scenarios, accompanied by a slight decrease in utilization rates. In these scenarios, the demand sinks are more closely tied to renewable energy availability, resulting in more flexible operations and, thus, lower demand sink capacity factors. However, total annual production increased in all scenarios.

We find that low-cost battery storage systems affect the low capital cost (<\$500/KW_{in}) demand sinks, resulting in higher installed capacity and increased annual production as compared to the scenario with mid-range battery storage costs. This shows that rather than competing with one another, battery storage systems can improve demand sink cost-effectiveness in a crucial part of the design space, which includes hydrogen electrolysis and resistive heating (and perhaps other potential demand sinks). The battery storage systems can effectively reduce the net system load when discharging, which then allows for a higher demand sink utilization, as discussed in Section 3.4.

Low-cost firm generation resources result in higher installed capacities for demand sinks with capital costs >\$500/KW_{in}. In low capital cost demand sink scenarios, cheaper firm resources significantly reduce

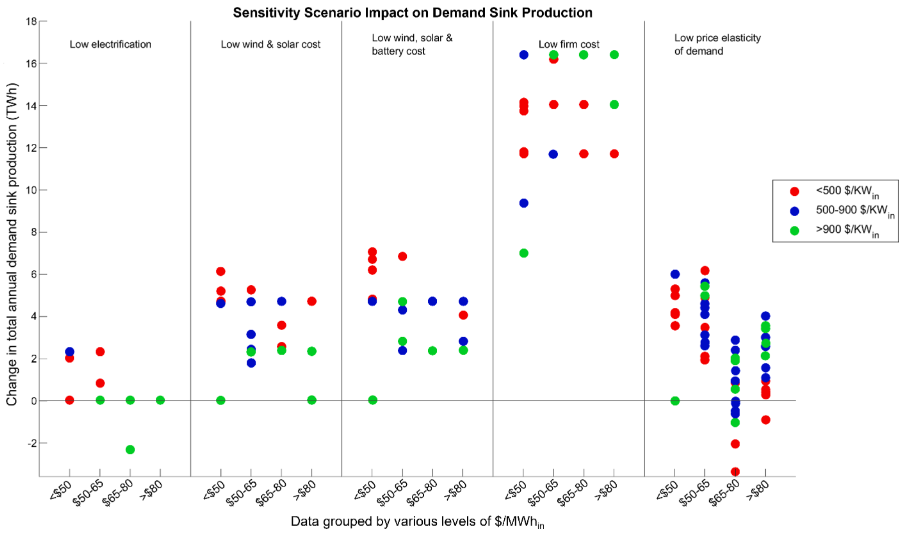

Fig. 5. Change in Demand Sink Annual Production Across Sensitivity Scenarios. Results are grouped by four levels of demand sink output product values and three levels of demand sink capital cost. The change in demand sink annual production is measured as an absolute change in TWh of production as compared to the same demand sink scenario without the sensitivity applied.

installed demand sink capacity, a change accompanied by increased utilization rates, as these technologies are now less tightly coupled with renewable generation. These low-cost firm generation scenarios allow for demand sink production from electricity directly from firm resources, which, together with lower average electricity prices, will also increase the total annual demand sink production. This indicates that if capable of producing electricity with a sufficiently low levelized cost, firm low-carbon resources offer a potential alternative or complement to variable renewables to fuel demand sinks.

Lastly, a lower price elasticity of demand (-0.6 instead of -0.8) was tested to observe its effects on demand sink results. Since a lower price elasticity of demand effectively causes demand to fall more slowly with increasing prices, demand sinks become slightly more favorable in this scenario, with overall increases in annual production across all cases. This sensitivity shows an important directionality; should one consider a demand sink with an output product that has a higher (or lower) price elasticity of demand instead, it would decrease (or increase) total annual demand sink production, all else equal.

4. Discussion

This study demonstrates that for an impactful level of demand sink capacity to be cost-effective in low-carbon power systems, we need sufficiently low demand sink capital cost and sufficiently high output product value. The design spaces modeled for hydrogen electrolysis, direct air capture, and flexible resistive heating as discussed in Section 4.1 are achievable before or by 2050 but require significant technological improvement to reduce capital costs. This reinforces the need for significant long-term investments, not only in the technologies themselves but also in their supporting infrastructure.

We find that including demand sinks in the power system can lead to significant changes in the installed capacity of wind and solar resources (0.95–1.9 MW additional wind and solar capacity for each MW of demand sink capacity). However, having a significant flexible load in the system does not result in significant displacement of firm generating capacity. Rather, we find that the magnitude of firm capacity reductions is only a small fraction of the demand sink capacity, where this reduction is mostly enabled through the additional renewable generation available during periods of highest net load, when demand sinks halt production. We additionally find that demand sinks do not significantly impact the average price of electricity in the system. Instead of delivering value by lowering electricity system costs, demand sinks enable greater deployment and utilization of low-cost but intermittent renewable energy to produce some other product of value.

While it has a minor impact on total system costs, demand sinks can also improve power system flexibility, as evidenced in cases with demand sinks with a $<\$800/KW_{in}$ capex, which can reduce the cycling of thermal plants by 5–50%, and cases with $<\$400/KW_{in}$ capex, which can decrease renewable curtailment (as a percentage of total potential renewable generating capacity) by 10–75%. When considering demand sinks with higher capital costs, these effects disappear, as those technologies will operate less flexibly overall.

When we consider demand sink output products, there is an inherent assumption of the existence of product demand in this study, which will be required for any demand sink technology to be viable. There needs to be a sufficiently large market for the output product produced, with consistent and preferably flexible demand for this product and/or low-cost product storage to enable consistent consumption despite intermittent production from demand sinks. In this study, we assume an identical, constant-slope price elasticity of demand between all scenarios, and we show that a lower (higher) elasticity will result in a higher (lower) total demand sink production. We note that we abstract away any level of potential seasonality in the demand for the output product, which has the potential to impact real-world demand sink operations.

We find that low capex demand sinks ($<\$500/KW_{in}$) ideally operate at a 30–40% utilization rate, with the possibility of prolonged periods of reduced production (as seen in Appendix Figure A.3). While high capex demand sinks ($>\$900/KW_{in}$) ideally operate at a 75–95% utilization rate, there can still be several days of reduced production in a given year during periods of high load and low renewable generation (and thus high marginal cost of electricity supply). This inherent intermittency in production, closely tied to renewable generation intermittency, reinforces the requirements for demand sinks to be flexible, for operations to be highly automated, and for the output product to be flexibly consumable and/or easily storable. If a technology does not meet these requirements, it will be challenging for it to effectively operate as a demand sink, as it will most likely be unable to respond to changes in electricity market prices efficiently.

4.1. *Application of results to real-world technologies*

To put the results of this study in perspective and apply them to real-world technologies and their potential future developments, Eq. (2) was used to convert the output product value parameter to physical products associated with potential demand sink technologies. The results of these conversions and their supporting assumptions can be found in Table 2. Note that the absolute values provided in the following table and subsequent results are subject to various techno-economic uncertainties arising from real-world interactions. Therefore, results should be used to gain a sense of the directionality and relative behavior of demand sink technologies under differing system compositions to avoid a false sense of precision.

To determine general guidelines for the conditions needed for certain technologies to achieve significant installed capacity, we take the results on the limits of the design spaces in the Northern and Southern system as shown in Fig. 6 to find the following capex - product price pairs for three high-potential technologies:

- Electrolysis: $150/KW_{in}$ capex with a hydrogen market price of \$1.40/kg, up till $300/KW_{in}$ and \$2.00/kg
- DAC: $1200/KW_{in}$ capex with a carbon market price of \$120/metric ton, up till $1500/KW_{in}$ and \$150/metric ton
- Resistive heating: $150/KW_{in}$ capex with a heating market price of \$7.50/MMBtu, up till $300/KW_{in}$ and \$13.40/MMBtu

Additionally, we can use Fig. 6 to assess the impact of the three example demand sinks considered in the study on the total system cost. We observe that including demand sinks in the power system can result in a cost reduction in the Southern system of at most 3% in the case of hydrogen electrolysis, 4% in the case of resistive heating, and 17% for DAC (versus 1%, 2%, and 10% in the Northern system, respectively).

The specific characteristics of infrastructure required to transport and store demand sink products will also affect the viability of candidate technologies. Each demand sink technology will require some level of supporting infrastructure and/or storage for its output product. This additional cost has been abstracted away in this study, partly because it is not immediately clear who that cost would fall on (see Section 5.4). Since many demand sink technologies create connections between the power system and other sectors, the costs for these technologies and supportive infrastructure, as well as the revenue of their output products, will likely be shared across sectors as well.

For some of the technologies highlighted in this study, such as DAC and resistive heating, the coupling of thermal storage or other product storage options may permit increased utilization of some portion of the capex, as it allows for some level of decoupling from the timing of low electricity prices. Storage solutions such as integrated heat storage for DAC could thus improve economic competitiveness in some circumstances (similar to the impact of low-cost battery energy storage systems observed in this study).

Each demand sink technology is also associated with output-specific market conditions as well, which are different for each technology:

- Hydrogen electrolysis: To compete with the traditional steam-methane reforming (SMR) hydrogen production process, higher natural gas prices and/or a price on carbon are needed. Without those conditions, our results indicate that hydrogen prices might be too low (<\$1.40/kg) for hydrogen electrolysis to become a valuable demand sink in the power system.
- DAC: Our results show that there is only one way for DAC to be a cost-effective demand sink technology, and that is through a sufficiently high price on carbon (>\$120/metric ton).
- Resistive heating: To compete with natural gas-fired boilers, relatively high natural gas prices (>\$7.13/MMBtu) and/or a price on carbon will be necessary.
- Bitcoin mining: For Bitcoin mining to become an effective demand sink, *lower* Bitcoin prices (<\$17,000 in 2021) will be needed to create an incentive to turn the mining equipment off at times of high electricity prices. While technically curtailable, if Bitcoin prices are sufficiently high, Bitcoin miners will have no financial incentive to turn the equipment off outside of rare periods of electricity supply scarcity. In this case, Bitcoin mining would effectively no longer qualify as a flexible demand sink, but rather a new source of interruptible electricity demand that curtails consumption only when electricity prices are very high. Computational requirements to mine a block of Bitcoin increase steadily over time (increasing 'hashrates'), which, if not compensated by deployment of more energy efficiency CPUs, could reduce the future value produced by Bitcoin mining per MWh_{in}, which could eventually encourage more flexible operation of mining rigs. However, at this point in time, Bitcoin mining seems unsuitable to serve as a demand sink technology as it will not operate with suitable flexibility.
- Desalination: Local conditions such as environmental regulations (dictating how to dispose of brine) and water prices are highly influential on the cost-effectiveness of desalination. However, if those conditions are favorable, desalination could be a valuable demand sink technology.

Apart from the economic impacts, demand sink technologies have the capability to help decarbonize multiple sectors at once. With net-zero carbon fuels like hydrogen through electrolysis, negative emissions through DAC, or zero-emission heat for industrial processes through resistive heating, demand sink impact stretches far beyond the power system itself [9,39]. On the contrary, not every demand sink technology inherently has such impacts; for example, cryptocurrency mining does not directly help to decarbonize any sector. In making investment or policy decisions related to demand sinks, these secondary impacts should be considered.

This study specifically evaluated a limited set of three high-potential demand sink technologies: hydrogen electrolysis, DAC, and resistive heating. Aside from Bitcoin mining and desalination, which were both briefly discussed as well, there is a broad range of other potential technologies that could operate as a demand sink in the low-carbon power system. Other possible technologies that could be considered as demand sinks include, but are not limited to:

Table 2

Conversion of the Output Value Parameter to per Unit Prices for Potential Output Products. Values that span the currently or future feasible design space have been highlighted based on existing research cited in Table 3. The values in this table are for illustrative and interpretative purposes only.[a]: Assuming 80% electrolyzer efficiency, \$1/MWh variable cost, and 130 MJ/kg H_2 heating value [29,30]. [b]: Assuming $\$25/t_{CO2}$ variable cost, and that it takes 1.316 MWh to capture 1 metric ton of CO_2 [31–33].[c]: Assuming 95% heater efficiency [34][d]: Using 2020 data to determine electricity consumption: 0.46M BTC mined with 80TWh electricity[35,36]. [e]: Assuming 3.2kWh/m^3, with a variable cost (non-electricity) of \$0.50/m^3 [37,38]. These values are illustrative, as desalination parameters are highly sensitive to geography.

$\$_{Value}/MWh_{in}$	10	20	30	40	50	60	70	80	90	100
Hydrogen Price (\$/kg)[a]	0.50	0.95	1.40	1.85	2.30	2.75	3.20	3.66	4.11	4.56
Captured Carbon Price (\$/metric ton)[b]	38.20	51.30	64.50	77.60	90.80	104.00	117.10	130.30	143.40	156.60
Resistive Heating (\$/MMBtu)[c]	3.09	6.17	9.26	12.34	15.43	18.51	21.60	24.68	27.77	30.85
2020 Bitcoin Price (\$)[d]	1739	3478	5217	6957	8696	10435	12174	13913	15652	17391
Desalinated Water (\$/m^3)[e]	0.53	0.56	0.60	0.63	0.66	0.69	0.72	0.76	0.79	0.82

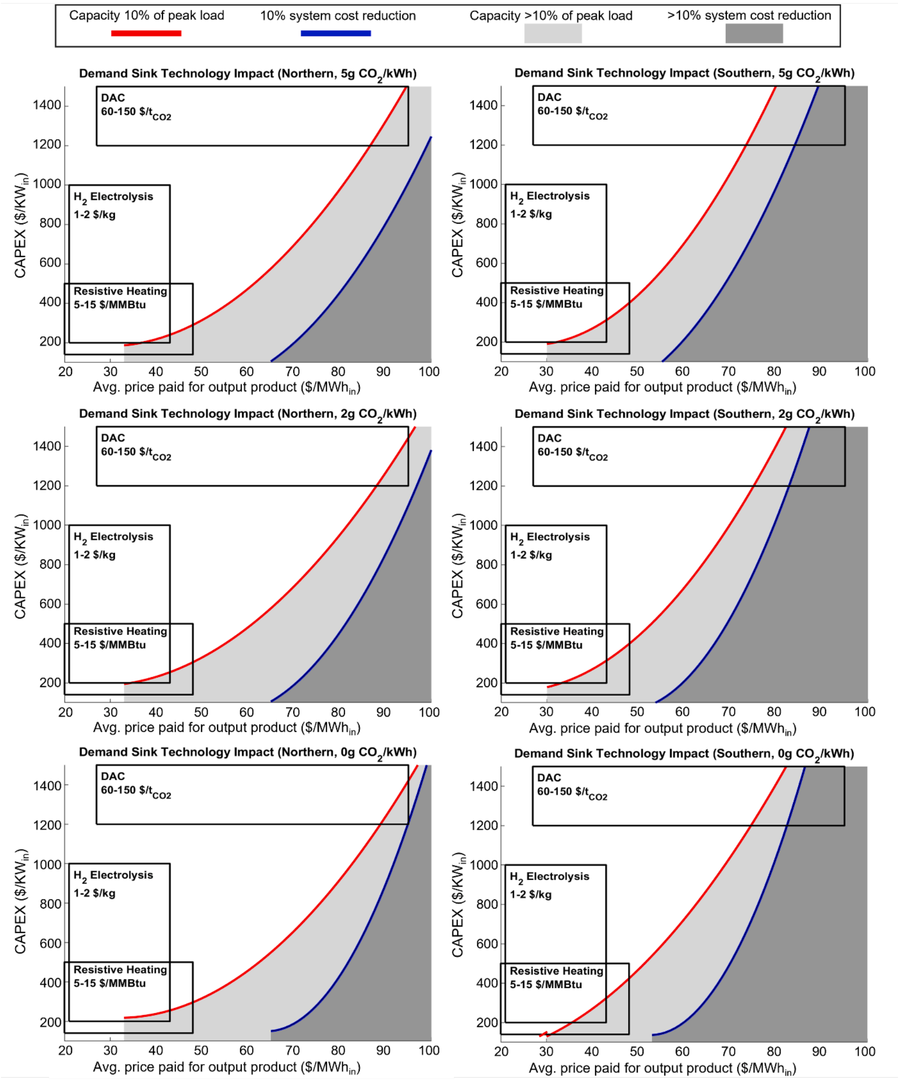

Fig. 6. Demand Sink Technology Design Space The left column shows the results in the Northern system, and the right column shows the Southern system. The stringency of the carbon dioxide emissions limit increases from top to bottom. The red line indicates the crossover to a 'significant' installed capacity, and the blue line indicates the crossover to a 'significant' system cost reduction. The rectangular boxes with potential demand sink technologies stretch both the current and future feasible design spaces of those technologies.

- Ground-source electric heat pumps (GSHP): Since GSHP have a high thermal storage potential, they can be operated flexibly and provide flexibility on a smaller scale than industrial resistive heating.
- Air-source electric heat pumps (ASHP): ASHP do not have the same inherent thermal storage potential as GSHP, but they can provide flexibility when used in conjunction with a natural gas-fired back-up or if coupled with a thermal storage media.
- Irrigation/Water pumping: While the economics are unclear, pumping processes are highly automated and water is easily storable, such that it could potentially function as a demand sink.
- Production of synthetic fuels, including methanation, Fischer-Tropsch, and various 'e-fuels' processes: These processes require a carbon-neutral source of CO_2 and a hydrogen source and can consume large amounts of energy to produce synthetic liquid or gaseous hydrocarbon fuels.
- Nuclear enrichment of fuels or spent nuclear fuel processing: This is a highly energy-intensive process, but the level of flexibility is unclear.

Each of the modeled and unmodeled technologies experiences different types of structural and parametric uncertainty, which must be studied extensively to fully understand their role in the future energy system. However, regardless of the specificity of certain technologies, one of the main advantages of this study is that the generic modeling strategy allows for any potential demand sink technology that falls within the requirements laid out in Section 1 to be evaluated using the presented results. Any such evaluation can provide valuable insights into the technology's potential impact on the power system and its operations within that system, as well as help inform sufficient output product value and concrete development targets for the technology's capital cost.

5. Methods

5.1. Demand sink technology design space

In this study, we evaluate the role and impact of a general class of flexible load technologies we call 'demand sinks' on the decarbonization of power systems. Through modeling a wide range of demand sink technology capital cost assumptions ($200–$1400/KW_{in}) as well as a wide range of output product value assumptions ($20–$100/MWh_{in}), we capture both the feasible design space of various potential demand sink technologies as well as currently infeasible combinations that are possibly achievable by the year 2050 or before with sufficient research and development. We specify the likely feasible design space for certain high-potential technologies, such as hydrogen electrolysis, DAC, and resistive heating, in Table 3.

The demand sink capital cost range was converted to an annuitized investment cost using a WACC of 7.1%, a 20-year financial asset life, and the inclusion of fixed operations and maintenance costs at 4% of the capital cost. Appendix Table D.5 facilitates the use of our results to evaluate technologies with different asset lifetime and/or WACC assumptions.

The various demand sink output product value scenarios were constructed using a constant-slope price elasticity of demand. This slope was calculated based on an elasticity of demand of -0.8 in the vicinity of a starting value of $\$50/\text{MWh}_{\text{in}}$ and a level of demand equal to 20% of the total annual system load. We approximate this slope with a stepwise function using fixed supply segment sizes that are each 1% of the total annual system load, resulting in a change in price of $3.125 between each segment. We use the same slope, bound to an artificially imposed supply limit, in each scenario modeled to normalize between them. We define each scenario by a base starting price from which we use this constant slope to generate supply segments: we generate lower-value segments until the product value falls to zero, and we generate higher-value segments until the demand falls to zero. This calculation produces a set of supply segments with associated values for each scenario. Within each scenario, the model can then freely decide in which segments to produce demand sink output, which then consequently sets the average output product value shown on the horizontal axis of the technology design space. We also model a low price elasticity sensitivity scenario with a constant slope based on an elasticity of -0.6 around the same starting price ($\$50/\text{MWh}_{\text{in}}$) and demand level (20% of total annual system load).

5.2. Scenarios modeled

To model the described range of $\$200–\$1400/\text{KW}_{\text{in}}$ of demand sink capital cost assumptions at $\$200/\text{KW}_{\text{in}}$ intervals, we use 7 scenarios (200, 400, 600, 800, 1000, 1200, and 1400 $\$/\text{KW}_{\text{in}}$). To encompass the range of average demand sink output product market values of $\$20–\$100/\text{MWh}_{\text{in}}$, we need a total of 14 scenarios, which are described by their base price corresponding to an annual supply limit of 20% of annual system electricity load (-15, 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, and 140 $\$/\text{MWh}_{\text{in}}$), as explained in the section above. This results in a total of 98 discrete capital cost - output value pairs. We model all these pairs across two regions: A 3-zone system with weather and demand characteristics of a region like New England ('Northern system'), and a 3-zone system with the weather and demand characteristics of a region like Texas ('Southern system'). Additionally, we test the effect of increasingly stringent CO_2 emissions limits through 3 additional cases applied to each scenario (5, 2, and 0 g CO_2/kWh), corresponding roughly to a 90%, 95%, and 100% reduction in emissions [49]. Altogether, this results in $98*3*2 = 588$ cases.

Table 3
Demand Sink Technology Economic Projections. *: The technology assumptions used to convert product market prices to these values are listed in Table 2.

Technology	Capex Range ($\$/\text{KW}_{\text{in}}$)	Capex Range (\$/unit)	Output Value Range ($\$/\text{MWh}_{\text{in}}$)*	Output Price Range (\$/unit)
Hydrogen Electrolysis	\$200–\$1000 [29,30, 40–42]	\$250–\$1250/ KW_{out}	\$21–\$42	\$1–\$2/kg [29,39,40, 43]
Direct Air Capture	\$1200–\$1500 [21, 31,39]	\$180–\$225/ $\text{t}_{\text{CO2}}\text{a}$	\$25–\$95	\$60–\$150/ t_{CO2} [39,44]
Resistive Heating	\$100–\$500 [45–47]	\$105–\$526/ KW_{heat}	\$20–\$48	\$5–\$15/ MMBtu [39, 48]

Furthermore, we run each of the 6 region-emissions limit scenarios without the option to build demand sinks as reference cases, of which the results are shown in Appendix Table B.1. These reference cases are used to study the demand sink impact on the power system, as all changes presented in this study are relative to those reference scenarios.

We then do additional sensitivity analysis on one scenario only, to limit the number of cases; we use the fully decarbonized, Northern system scenario only, since that scenario is most sensitive to changes in conditions - it has the highest average price of electricity and thus presents the least favorable conditions for demand sinks. With a total of 5 different sensitivity scenarios, modeled across a more narrow design space of $\$200–\$1000/\text{KW}_{\text{in}}$ and $\$20–\$90/\text{MWh}_{\text{in}}$, we model an additional 275 cases for this sensitivity analysis. Each sensitivity scenario setup is explained in more detail below.

The base case assumes a high electrification of transportation, space and water heating energy demands with stocks and load profiles from [4]. High electrification results in both more demand response flexibility (via flexible EV charging and heat pump loads) and gives a higher overall annual load with greater winter and overnight demand. To understand the effects of this assumption on the results, we test a low electrification scenario (corresponding to a 26.8% reduction in total annual load) with a 87.2% reduction in flexible, shiftable load, as further detailed in Appendix E [57–61].

All available generating resources across cases are based on data from the 'moderate scenario' for the year 2050 in NREL's Annual Technology Baseline 2020 [50,54–56], as shown in Appendix Tables D.1 and D.2. To model low resource cost scenarios, which correspond to significant technology developments over the coming decades, we use the 'Advanced' scenario where available. That scenario is available for wind, solar, and Li-ion battery storage systems resources, but not for nuclear and natural gas with CCS. Therefore, we implement a low-cost firm generation scenario by imposing a 50% fixed cost reduction for nuclear and a 25% fixed cost reduction for natural gas with CCS as compared to the ATB. Since we place emphasis on the directionality of the outcome rather than the absolute change in demand sink production, the magnitude of the cost reduction itself is of secondary importance, given that it is sufficiently large to observe a change in the model results. The corresponding low-cost assumptions for these sensitivity scenarios can be found in Appendix Table D.3.

5.3. Modeling setup

To evaluate the general class of demand sink technologies, this study employs the GenX electricity system capacity expansion optimization model with high temporal resolution (8760h) and detailed operating decisions and constraints using a cost-minimizing objective. This model is described in detail in [26], but an overview is provided in Appendix G, and its configuration for this study is described in more detail in Appendix F [62–65], with a setup similar to the one used in [3]. In its application in this study, the model considered detailed operating characteristics such as thermal power plant cycling costs and constraints (unit commitment), limits on hourly changes in power output (ramp limits) and minimum stable output levels, as well as intertemporal constraints on energy storage. The model also captured a full year of hourly chronological variability of electricity demand and renewable resource availability. The linear programming model selected the cost-minimizing set of electricity generation and storage investments and operating decisions to meet forecast electricity demand reliably over the course of a future year, subject to specified policy constraints (e.g., CO_2 emissions limits).

5.3.1. Demand sink implementation

We model the generic demand sink technology as a continuous capacity decision that can be installed in every model zone at a fixed capital cost. Every MW of demand sink can then be used to produce output at any utilization rate at any hour, with 100% hourly ramp rates and without constraints on minimum power output or on minimum up/down times. Each MWh of output product will be produced in a particular demand sink output product market segment, as chosen by the model. Each fixed-size segment has an annual supply limit and an associated market price, creating a step-wise approximation of a demand curve for the product. This market price for each MWh of generation is then directly used as demand sink 'revenue', which is added to the model objective function alongside the demand sink capital cost. In Tables 4 and 5 below, the respective decision variables and model parameters added to GenX for this demand sink implementation are shown. Note that we introduce one new set $q \in Q$ where q denotes a demand sink market segment with an associated output product value and Q is the set of all market segments.

The original GenX objective function in Eq.G.1 must be modified to include new investment and revenue variables associated with the demand sinks. It is therefore updated with additional terms to account for the total cost of demand sink-related capacity investments ($y_z^{DS} \cdot c^{DS}$) and the total revenue of demands sink production ($x_q^{supply} \cdot x_q^{value}$) in Eq. (3).

$$\min_{y,x} \Bigg(\tag{3a}$$

$$\sum_{g \in G} \left(y_g^{P+} \cdot c_g^{Pi} \cdot \overline{y}_g^{P\Delta} + y_g^{P\Sigma} \cdot c_g^{Pom} \right) + \sum_{l \in L} \left(y_l^{F+} \cdot c_l^{Fi} \right) + \tag{3b}$$

$$\sum_{w \in W} \sum_{h \in H} \left(\sum_{g \in G} \left(x_{g,h,w}^{inj} \cdot \left(c_g^{Po} + c_g^{f} \right) \right) + \sum_{g \in O} \left(x_{g,h,w}^{wdw} \cdot c_g^{Po} \right) + \sum_{z \in Z} \sum_{s \in S} x_{s,h,w,z}^{nse} \cdot n_s^{slope} \right) + \tag{3c}$$

$$\sum_{w \in W} \sum_{h \in H} \left(\sum_{g \in UC} x_{g,h,w}^{start} \cdot c_g^{st} \right) \Bigg) + \tag{3d}$$

$$\sum_{z \in Z} \left(y_z^{DS} \cdot c^{DS} \right) - \sum_{q \in Q} \left(x_q^{supply} \cdot x_q^{value} \right) \tag{3e}$$

New investment and production decisions require additional constraints to the problem described in the previous section. While the installed demand sink capacity is not limited, production is limited in each market segment by the maximum supply in that segment through Eq. (4a). Moreover, the total annual supply is limited by the total annual production across all zones in Eq. (4b). Lastly, demand sink production is limited by the installed capacity in each zone in Eq. (4c).

$$x_q^{supply} \leq x_q^{C\wedge} \quad \forall q \in Q \tag{4a}$$

$$\sum_{q \in Q} \left(x_q^{supply} \right) \leq \sum_{h \in H} \sum_{z \in Z} \sum_{w \in W} \left(x_{t,z,w}^{prod} \right) \tag{4b}$$

$$x_{h,z,w}^{prod} \leq y_z^{DS} \quad \forall h \in H, z \in Z, w \in W \tag{4c}$$

5.4. Limitations

We note several limitations of this work. First, we make several abstractions to enable the evaluation of demand sinks as a generic class of resource across a wide potential design space. Each potential demand sink technology will require some level of supporting infrastructure and/or storage for its output product. This additional cost has been abstracted away in this study, partly because it is not immediately clear who that cost would fall on. Since many demand sink technologies create connections between the power system and other sectors, the costs for these technologies, as well as the revenue of their output products, will likely be shared across sectors as well. This paper can form a basis for future work that could focus on a discrete subset of technologies that fall within attractive portions of the design space identified in this study, evaluating each technology in more detail and including investments related to storage and supporting infrastructure. This work will have to consider impacts beyond just the power system and represent the shared economics between sectors to more accurately represent the costs and value of demand sink technologies. Such work could also provide a more detailed evaluation of the demand sink output product market conditions required to support cost-effective demand sink operations. We also underscore the importance of considering not only the capacity of demand sink technologies to produce valuable products but also their flexibility in response to market dynamics and grid conditions. Resistive heating systems and proton exchange membrane electrolyzers exhibit significant operating flexibility, enabling rapid adjustments to energy consumption. However, end-users may require a constant or regular supply of heat or hydrogen. In such cases, resistive heating may be installed in a hybrid configuration alongside conventional heat sources (e.g., combustion) and/or coupled with thermal energy storage to consume electricity while delivering a constant heat supply flexibly. Similarly, hydrogen storage may buffer output from flexible hydrogen production and ensure consistent supply to end users. Other technologies, such as direct air capture (DAC)and desalination, generally face operating constraints that limit their flexibility but may also be coupled with energy storage (e.g., thermal storage to decouple solvent or sorbent regeneration from electricity consumption in DAC systems). In all cases, ensuring flexible operation as an electricity demand sink while respecting constraints imposed by engineering considerations or market demands could entail greater capital expenditures, which can be factored into the analysis herein by considering a higher cost per kW within the design space considered. Understanding these technology-specific flexibility strategies and associated costs in more detail will be crucial for devising effective deployment strategies that capitalize on each potential demand sink's unique strengths while mitigating potential inflexibility challenges (as noted in Section 4). These heterogeneous market characteristics were also abstracted away in this study but can have a significant impact on demand sink operations and value in the system. Similarly, this work does not consider the impact of transmission constraints on the value and market adoption of demand sink technologies.

Table 4

Additional Decision Variables to Model a Generic Demand Sink Technology.

Notation	Description
$x_{h,z,w}^{prod}$	Demand sink production in zone z during hour h in sub-period w
y_z^{DS}	Demand sink capacity installed in zone z
x_q^{supply}	Total demand sink production in market segment q

Table 5

Additional Parameters to Model a Generic Demand Sink Technology.

Notation	Description
c^{DS}	Annuity of capital cost for demand sink capacity investments
$x_q^{C\wedge}$	Maximum demand sink production in market segment q
x_q^{value}	Demand sink output product value in market segment q

Second, we evaluate only techno-economic-related considerations in this optimization framework. All resources considered herein, including the wide range of demand sink technologies, have environmental and societal impacts or entail risks or hazards that may constrain their development, differentiate them on non-cost related dimensions, and ultimately impact their deployment. Promising demand sink technologies should be further evaluated along a variety of non-cost related dimensions, including their own relative risks or impacts as well as their potential to change the aggregate portfolio of electricity resources and mitigate or exacerbate associated non-cost related impacts.

Lastly, some additional limitations inherent to the specific configuration of the GenX model employed in this study are detailed in Appendix F.

CRediT authorship contribution statement

Sam van der Jagt: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Neha Patankar:** Data curation, Investigation, Project administration, Supervision, Writing – review & editing. **Jesse D. Jenkins:** Conceptualization, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

Jesse Jenkins reports a relationship with DeSolve that includes: equity or stocks. Jesse Jenkins reports a relationship with Eavor Technologies Inc. and Rondo Energy Inc. that includes advisory board membership, equity or stocks. Current consulting clients include MUUS Climate Partners and Energy Impact Partners.

Data Availability

Data will be made available on request.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.egycc.2024.100132.

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