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Solar Thermoelectricity via Advanced Latent Heat Storage: A Cost-Effective Small-Scale CSP Application

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Abstract. We are developing a novel concentrating solar electricity-generating technology that is both modular and dispatchable. Solar ThermoElectricity via Advanced Latent heat Storage (STEALS) uses concentrated solar flux to generate high-temperature thermal energy, which directly converts to electricity via thermoelectric generators (TEGs), stored within a phase-change material (PCM) for electricity generation at a later time, or both allowing for simultaneous charging of the PCM and electricity generation. STEALS has inherent features that drive its cost-competitive scale to be much smaller than current commercial concentrating solar power (CSP) plants. Most obvious is modularity of the solid-state TEG, which favors smaller scales in the kilowatt range as compared to CSP steam turbines, which are minimally 50 MW_e for commercial power plants. Here, we present techno-economic and market analyses that show STEALS can be a cost-effective electricity-generating technology with particular appeal to small-scale microgrid applications. We evaluated levelized cost of energy (LCOE) for STEALS and for a comparable photovoltaic (PV) system with battery storage. For STEALS, we estimated capital costs and the LCOE as functions of the type of PCM including the use of recycled aluminum alloys, and evaluated the cost tradeoffs between plasma spray coatings and solution-based boron coatings that are applied to the wetted surfaces of the PCM subsystem. We developed a probabilistic cost model that accounts for uncertainties in the cost and performance inputs to the LCOE estimation. Our probabilistic model estimated LCOE for a 100-kW_e STEALS system that had 5 hours of thermal storage and 8–10 hours of total daily power generation. For these cases, the solar multiple for the heliostat field varied between 1.12 and 1.5. We identified microgrids as a likely market for the STEALS system. We characterized microgrid markets in terms of nominal power, dispatchability, geographic location, and customer type, and specified additional features for STEALS that are needed to meet the needs of this growing power market.

INTRODUCTION

Recently deployed concentrating solar power (CSP) tower technology in the United States includes Solar Reserve's Crescent Dunes power tower (110 MW_e) [1], and BrightSource's Ivanpah Power Park (3x130 MW_e) [2]. Solar ThermoElectricity via Advanced Latent heat Storage (STEALS) was conceived as a tower-mounted CSP technology that targets smaller-scale power markets. Several small-scale power towers (1-3 MW_e) that employ turbines and thermal storage are operating around the world including Dahan Power Plant in China (saturated steam), Greenway Mersin in Turkey (molten salt), and Jemalong (liquid sodium) and Lake Cargelligo (graphite) in Australia [3]. STEALS employs solid-state thermoelectric generators (TEGs), which have no moving parts and are commercially available at power ratings down to a few watts. TEG-based power generation may include thermal

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storage using a phase-change material (PCM), which makes its energy dispatchable and distinguishes it from photovoltaic (PV) variable power generation.

Figure 1 shows the integrated design for the STEALS system that is based on the heliostat field and tower point-focus geometry. STEALS is a fully integrated design that includes the receiver, PCM thermal storage, thermal valve, TEGs, and heat rejection in a single module that is located at the top of the tower. This design eliminates piping, valves, and pumps associated with circulating heat-transfer fluid from a tower-mounted receiver to thermal-storage and power-block subsystems that are normally located at ground level. In Fig. 1, concentrated sunlight from the heliostat field is absorbed by a slightly down-facing receiver (with a receiver elevation angle of -35 degrees). The captured thermal energy is delivered to an array of thermoelectric generators for immediate electricity generation, used to charge the PCM for thermal energy storage, or split between the two to provide simultaneous electricity generation and storage. Heat transfer from the absorber and within the PCM is facilitated with vertical heat pipes.

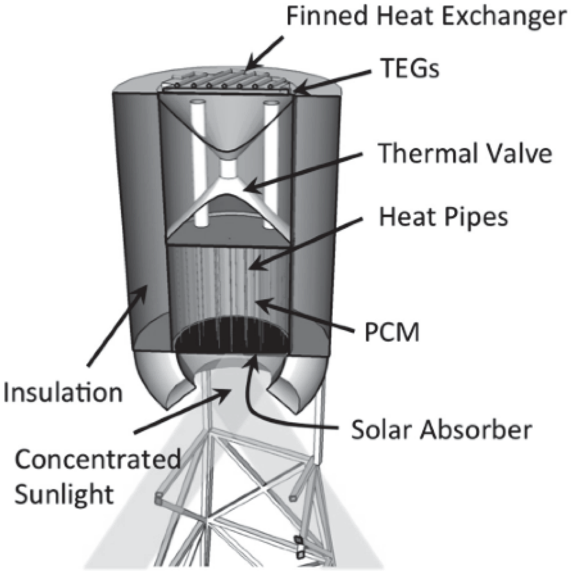

FIGURE 1. Schematic of the STEALS system: an integrated receiver/thermal storage/thermal valve/generator/heat exchanger module atop a trussed tower within a small heliostat field [4].

To enable dispatchability, we designed a thermal valve, an actively controlled hourglass-shaped thermosyphon that regulates the level of thermal power delivered to the TEG array for on-demand electricity generation. We have built a laboratory-scale prototype STEALS module to demonstrate the functionality of this design.

The integrated tower-mounted STEALS system has several features that make it attractive for smaller electricity markets and that contrast its strengths relative to commercial CSP technologies.

- **Modularity:** TEGs are solid-state devices that generate electric power from the flow of thermal energy through the device and across the resulting temperature drop. They are inherently modular due to their simple design and operation. This feature allows TEGs to be practically sized for small power systems without compromising their efficiency or cost.
- **PCM energy storage:** Latent-heat thermal energy storage allows for higher volumetric storage densities than sensible-heat storage systems due to the PCM's high heat of fusion. PCM storage has nearly isothermal operation, providing thermal energy to the TEGs at the optimum temperature for electricity generation.
- **Power-block integration:** TEG modularity and high stored energy density allow the power-block components to be integrated into a single unit that is located at the top of the tower. This arrangement eliminates piping, valves, and fluid pumps that are common to standard power-tower configurations.
- **Dispatchability:** The use of a thermal valve with PCM storage regulates the flow of thermal energy to the TEG and allows STEALS to generate electricity during off-sun hours. This feature eliminates or reduces intermittent power generation due to passing clouds, and allows electricity generation to meet demand.
- **Simple design and operation:** The STEALS system has few moving parts, creating a highly reliable system with low operation and maintenance costs. TEGs are solid-state devices that have been shown to operate

without maintenance for decades on NASA missions [5]. Likewise, the PCM system is stationary, not requiring active pumping.

These features combine to make this small-scale CSP system both technically feasible and economically attractive for power markets in the range of 10 kW_e to 1 MW_e.

OBJECTIVES

Our objectives for this analysis were to 1) determine the levelized cost of energy (LCOE) for a 100-kW_e STEALS system with 5 hours of thermal storage and 8–10 hours total power generation per day, and 2) identify and characterize likely markets for a power-generating system of this size and hours of dispatchable energy delivery. We chose 5 hours of thermal storage based on the need to provide off-sun power generation during peak hours in the late afternoon and early evening.

TECHNOECONOMIC ANALYSIS

We established the LCOE metric for this system by evaluating the LCOE for a comparable 100 kW_e PV system with 5 hours of battery energy storage. We used the PVWatts, Single owner module in SAM version 2015.1.30 [6] with the system specifications and component costs listed in Table 1. All financial parameters were the standard values for the PVWatts, Single owner module.

TABLE 1: Specifications for 100 kW_e PV system with battery storage

Specification for 100 kW_e PV system	Value
Meteorological location	Daggett, CA
Array configuration	Single axis tracking
PV annual degradation	0.5%
DC to AC ratio	1.1
Inverter losses	4%
Battery charge/discharge losses	10%
Other system losses	12.6%
Battery replacements	1
PV module cost	\$0.71/KW_{dc}
Inverter cost	\$0.10/KW_{dc}
Installed battery cost range	\$190-\$550/kWh_{dc}
Operating & Maintenance	\$15/kW-yr

Estimates for near-term stationary battery costs vary widely, so we evaluated system LCOE using installed battery costs that ranged from \$190/kWh to \$550/kWh. We assumed one battery replacement over the 30-year operating lifetime of the system (15-year battery life). With these assumptions, we obtained LCOEs that ranged from \$0.15/kWh to \$0.25/kWh for this system. We chose a target LCOE for STEALS of \$0.12/kWh to be well below the LCOE range for PV with battery storage.

For the STEALS analysis, we generated design specifications that defined the characteristics and requirements for the STEALS system. We chose nominal power of 100 kW_e because it was within the range of sizes (10 kW_e–1 MW_e) that we initially considered for STEALS markets. We targeted 8-10 hours of daily electricity generation to address intermediate load markets, with 5 hours of thermal storage so the system would have a high level of dispatchability. All specifications are listed in Table 2, and are consistent with those used in standard CSP TEA analysis.

We performed a detailed design of all subsystems and components shown in Fig. 1. The receiver aperture was based on the 100-kW_e power rating and resulted in a combined receiver optical and thermal efficiency of 96 percent at design point (95 percent on an annual basis). The relatively small heliostat field size, cavity receiver design, low receiver temperature of 650°C, and high concentration ratio of ~1350 allows for higher receiver efficiency than normally found in larger external receivers [7]. We designed our PCM storage system to have 5 hours of thermal storage and included sodium heat pipes to achieve the required power density for delivering thermal power to the

TEG. We included the thermosyphon thermal valve in the design so that thermal power to the TEG could be regulated for dispatchable power delivery. The TEG was sized to generate 100 kW_e at design operating conditions. To reject heat at the required rate, we designed and sized a radiator that cooled the backside of the TEG with circulating water/glycol coolant. Heat rejection to ambient air was accomplished using fan-cooled fins. We estimated the parasitic power requirements for pumping the liquid coolant and powering the fan.

We determined the optimal heliostat-field size that minimizes the combined costs of the heliostat field and the tower. This optimization was performed using SolarPILOT, a heliostat-field optimization code developed at NREL. We determined optimal field layouts and tower heights for a range of TEG efficiencies from 11% to 17%, because the optimal field size and tower height vary significantly with the thermal power rating of the solar field. The 11% efficiency represents the current state-of-the-art TEG whereas 17% represents the highest possible TEG efficiency that is thought achievable in the next 5 years. Our design point solar-field optical efficiency varied with field size and layout between 82-85 percent for different configurations. This efficiency included cosine, attenuation, blocking and shading, and intercept efficiencies. Our combined thermal storage and valve efficiency was 95 percent.

TABLE 2: Specifications for STEALS system

Specification	Value
Net power	100 kW_e
Thermal storage/off-sun generation	~5 hours
On-sun generation	~3-5 hours
Solar multiple	1.12–1.5
Capacity factor	31.4%–38.1%
Meteorological location	Daggett, CA
TEG cooling method	Dry
TEG rejection temperature	63°C
Ambient temperature	37°C

We used probabilistic cost analysis to estimate LCOE for our STEALS 100-kW_e system. Probabilistic cost analysis is the standard method for evaluating LCOE within the DOE Solar Program [8–10]. This method accounts for uncertainties in cost and performance inputs when evaluating a new technology. The method assigns probability distributions to these inputs rather than a single value. Table 3 lists the distribution ranges for the cost and performance inputs that we used to evaluate the 100-kW_e system (2015 $U.S.). Custom component costs were based on vendor quotes for materials and fabrication. Heliostat cost range was based from the SunShot Vision Study [11] and TEG costs were obtained from the TEG manufacturing cost studies [12, 13]. The output from the model is an LCOE distribution that is statistically analyzed to determine the mean and standard deviation. We sampled the input distributions using the Latin-Hypercube Sampling (LHS) method [14]. The sampling algorithm sampled each input distribution M (1,000) times generating an M x N matrix where M is the number of sample sets and N is the number of cost and performance inputs. These inputs were used in the System Advisor Model (SAM) to generate 1,000 LCOEs for each STEALS configuration.

TABLE 3: Distribution ranges for cost and performance inputs use in probabilistic LCOE analysis.

Cost & Performance Inputs	Distribution Range
Heliostat field cost ($\$/m^2$)	50 - 125
Tower cost ($\$/kW_e$)	154 - 344
TES/receiver cost - 4 options ($\$/kWh_t$)	15 - 29
Valve cost ($\$/kW_t$)	148 - 277
TEG cost ($\$/W_e$)	0.25 – 0.625
HX cost constant ($\$/kW_t$)	32 - 79
O&M ($\$/kW_e/yr$)	20 - 40
TEG efficiency (kW_e/kW_t)	0.11 – 0.17

Figure 2 shows the programming modules used to execute this method. We used Python to generate the input probability distributions and input sample matrix. We used the LK Scripting Language to pass the input sample sets to a SAM module to determine LCOE, and to pass the LCOE outputs from SAM to a second Python module that calculated regression coefficients for the inputs. Our Generic CSP SAM module used the system specifications listed in Table 2, and the financial parameters listed in Table 4. Both are consistent with those used by the Solar CSP Program to estimate LCOEs for CSP plants.

Over the course of our analysis, we identified two modifications to the PCM storage module that would reduce the capital cost of the thermal storage subsystem. Implementing one or both modifications generated four options for the PCM module. The options included the PCM material and cost, and the protective coating for the wetted surfaces.

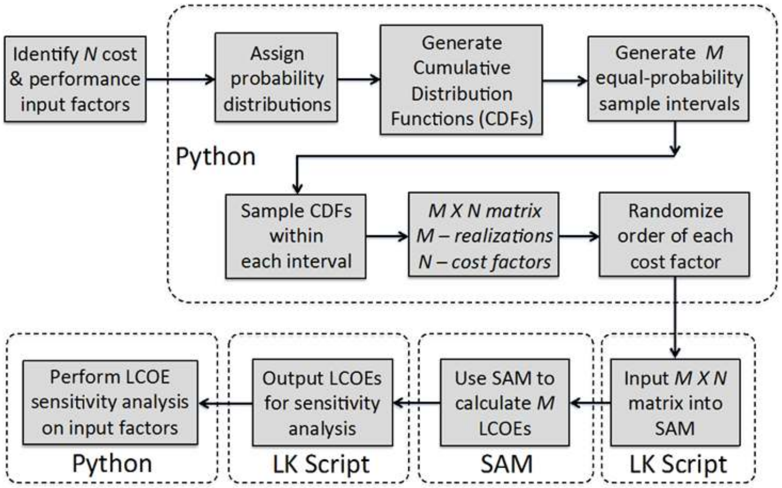

FIGURE 2: Probabilistic analysis data flow for LCOE estimation.

We estimated LCOEs for the 100-kWe STEALS system using these four thermal-storage options:

1. Primary aluminum PCM with plasma-coated wetted surfaces
2. Recycled aluminum PCM with plasma-coated wetted surfaces
3. Primary aluminum PCM with solution-based, boron-coated surfaces
4. Recycled aluminum PCM with solution-based, boron-coated surfaces

Option 1 was our original configuration for the PCM storage system. For each option, we used solar multiples of 1.12, 1.3, and 1.5. The lower value represents a plant that has 5 hours per day off-sun operation and about 3 hours per day of on-sun operation. The higher value represents a plant that has 5 hours per day off-sun operation and about 5 hours per day on-sun operation.

TABLE 4: Financial parameters for STEALS LCOE analysis.

Financial Parameter	Value
Plant life	25 years
Annual inflation rate	2.5%
Real discount rate	5.5%
Federal/state tax rate	35%/7%
Sales tax	5% of 78% of DC
Project loan period and interest rate	18 years, 7%
Debt fraction	0.6
Required IRR and DSCR	11% and 1.3
MACRS	Yes
Investment tax credit	0%
Land cost	$10,000 per acre
Site improvement cost	\$10/m^2

Figure 3 shows the histogram of LCOE for 1,000 outcomes for Option 4 using a solar multiple of 1.3. Histograms for all combinations of options and solar multiples had similar distributions. Option 4 generated occurrences for implementing both cost-saving measures in the thermal storage subsystem and generated a mean LCOE of 11.8¢/kWh. The 1,000 outcomes shown in Figure 3 had a standard deviation of 1.21¢/kWh, and a 95% confidence interval of 11.7¢/kWh to 11.9¢/kWh. These statistics assume the cost and performance distributions listed in Table 3. Results shown in Table 5 had similar standard deviations and 95% confidence intervals.

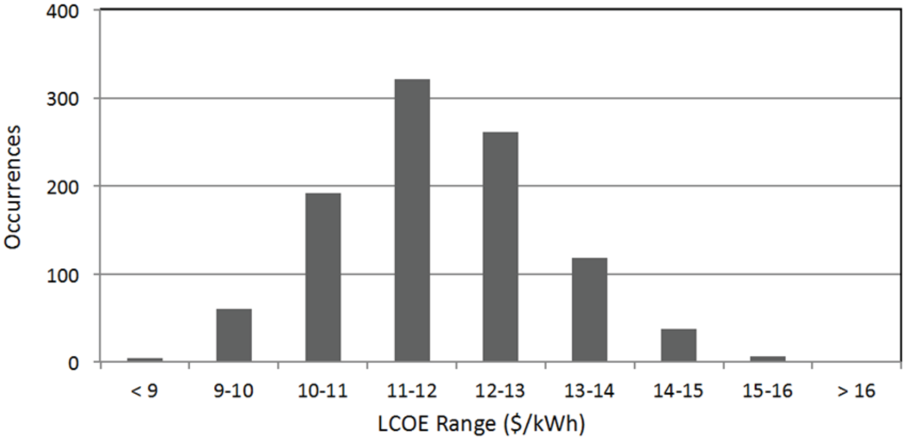

FIGURE 3: Histogram of LCOEs for Option 4 with 1.3 solar multiple.

Table 5 shows a summary of mean LCOEs for Options 1–4 with solar multiples of 1.12–1.5. Table 5 shows two trends: 1) LCOE decreased going from Option 1 to Option 4, and 2) LCOE decreases with increasing solar multiple. The first trend results from the cost savings incurred by using less-expensive PCM material and protective coating. The second trend results because larger solar multiples mean larger heliostat-field size relative to the nominal power rating of the receiver. The larger field size increases the cost of the heliostat field but also increases power-block utilization and annual energy production. This effect is especially true for systems that have thermal storage because the storage system allows the power block to better use the abundant solar resource that is available during the summer months. The net effect of larger solar multiples is to decrease LCOE. However, the additional electricity typically has lower value so the decreased LCOE does not necessarily generate improved plant economics. Based on near-term battery costs, these results indicate that STEALS is more cost effective than PV with battery storage for this system specification.

TABLE 5: Summary of mean LCOE (¢/kWh) for aluminum alloy based PCM STEALS

Option	Description	SM = 1.12	SM = 1.3	SM = 1.5
1	New Al, Plasma coating	14.3	13.4	12.9
2	Recycled Al, Plasma coating	13.4	12.6	12.2
3	New Al, Solution coating	13.4	12.6	12.2
4	Recycled Al, Solution coating	12.5	11.8	11.4

We calculated standard regression coefficients (SRCs) [15] for the input factors to the probabilistic model for Options 1–4. Figure 4 shows the rank ordering of normalized coefficients for the input factors for Options 1 with SM = 1.3. All options showed similar values and ordering. LCOE is most sensitive to TEG efficiency because all subsystem sizes and costs decrease as TEG efficiency increases. Besides TEG efficiency, LCOE is most sensitive to solar-field cost and TEG cost. These costs are the greatest contributors to the system cost and represent the best opportunities for capital cost reduction, particularly reductions in the heliostat-field costs. O&M cost also has a significant impact on LCOE and must be kept at a minimum for the small system sizes that we are targeting. The remaining cost and performance inputs have little impact on LCOE. These results show that increasing TEG efficiency, and reducing solar field and TEG costs achieved the greatest impact on LCOE.

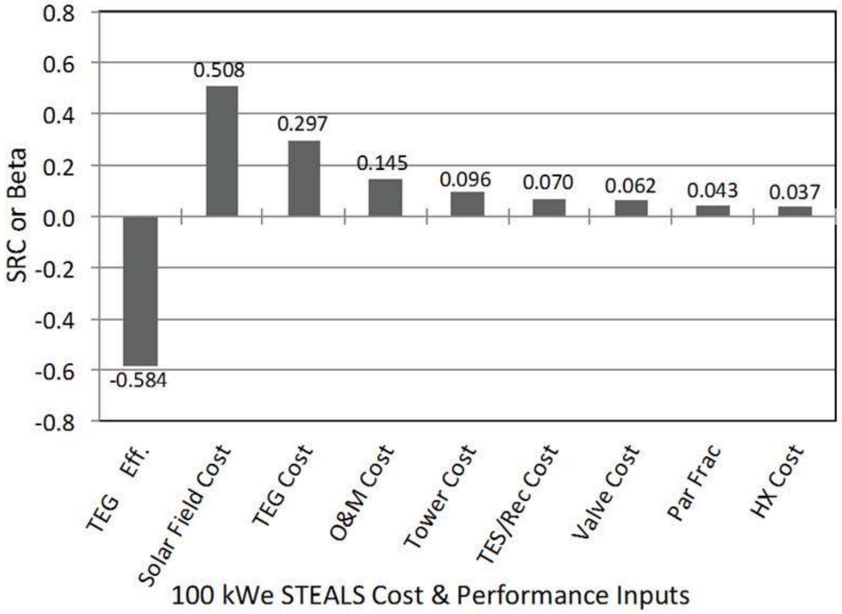

FIGURE 4: Regression coefficients for input factors for metals-based STEALS Option 1

MARKET ANALYSIS

STEALS market analysis identified microgrid markets as the best application for STEALS over the next 5 years. Microgrid markets in the U.S. and worldwide are a rapidly growing segment of overall electricity production [16]. End users include isolated communities (islands) and facilities (mining operation), and more recently, communities that have access to the utility grid but want to generate their electricity locally with renewable power generation. Current microgrid deployments in the U.S. are categorized by grid connection, capacity, type of power generation, and end-user type. Microgrids are typically remote and may be either grid-connected (edge grid) or off-grid (islanded). Half of current microgrids are less than 1 MW_e. Microgrids that are less than 1 MW_e are considered the best market for future installations.

We extended our STEALS LCOE analysis to evaluate system sizes in the range of 20 kW_e to 1 MW_e. Our analysis showed that LCOE is essentially constant within this range and the minimum LCOE occurs at 100 kW_e. A minimum occurs because of the tradeoff between a reduction in optical efficiency (and reduced heliostat field cost) and an improvement in storage efficiency (because of improved surface area: volume ratio). We believe we have a good market match for STEALS technology because an increasing fraction of new installations will use renewable technology and most future installations are expected to be less than 1 MW_e. End-user markets include residential communities, public institutions, commercial applications, universities, military installations, and islands. Microgrid deployments for hospitals, military installations, and other critical public institutions are motivated by need for reliability. Isolated (island) installations are motivated by cost reduction and reliability. Community installations are motivated by the desire to generate electricity locally from renewable sources [17].

Microgrid installations commonly occur at extreme locations, such as a military installation on Kodiak Island, Alaska; a remote gold/copper mining operation in Australia; and an isolated field installation on Ross Island, Antarctica. Geographic location, specifically latitude, is a key consideration for STEALS because heliostat-field optical efficiency decreases significantly at high latitudes. Greater seasonal variation in solar resource at high latitudes also adversely impacts LCOE for systems with high capacity factors that are designed to deliver dispatchable electricity year round.

Off-grid microgrids that are located at high latitudes require large solar multiples and many hours of thermal storage to achieve high capacity factors and dispatchability. Additionally, the large thermal storage requirement for these systems may not be practically feasible due to the weight of the PCM storage subsystem that is integrated into the complete system and mounted at the top of the tower. For these reasons, we are considering locations for STEALS at moderate to low latitudes, particularly for off-grid applications.

CONCLUSIONS

We completed our initial system design, techno-economic analysis, and market analysis of STEALS. These efforts were performed in parallel with continuous feedback, so our end result was a functional design that has unique features and benefits relative to current commercial CSP and PV generating systems. Relative to CSP, STEALS has a simple design that integrates the receiver, thermal storage, and power block components at the top of the tower. The use of TEG solid-state devices for power generation allows for favorable capital costs at small scales, and the inherently modular design while maintaining simple operation and low maintenance costs. STEALS has a clear advantage relative to PV systems of offering dispatchable electricity generation. STEALS has favorable economics relative to PV with battery storage based on current and near-term costs of batteries for the next 4 years, which is our timeframe for completion of the first on-sun demonstration of this system.

Our TEA showed that this configuration has favorable LCOE at scales between 20 kW_e and 1 MW_e, which matches the most common nominal power ratings for microgrid installations. We identified off-grid and edge-grid microgrids as the most promising markets for this STEALS due to the expectation that installed microgrid capacity in the U.S. will more than double from its current level by 2020. In addition, an increasing fraction of new microgrid installations are expected to use renewable power. This demand is driven mostly by the desire for small, local, community-based generating capacity. Dispatchable electricity delivery is a key feature that STEALS brings to these markets, and it allows STEALS to maintain a competitive advantage over comparable PV systems.

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