Hybrid Photovoltaic/Thermal Solar Plus Storage Cogeneration Systems

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ABSTRACT

Current PV technology is inefficient, converting only about 21% of solar energy into usable power at the ideal temperature of 25 °C. Panels often reach temperatures of 65–75 °C, significantly reducing production. Still, commercial and industrial PV plus storage is expected to grow from $8.6 billion in 2020 to $30.1 billion in 2030. Icarus RT, Inc. offers a novel photovoltaic/thermal (PV/T) solar plus storage cogeneration system for commercial and utility scale applications. The hybrid system cools PV panels by extracting waste heat, collecting and storing thermal energy, and converting thermal energy into hot water and/or additional electric power on demand (i.e., after sunset) using an Organic Rankine Cycle (ORC). Overall, Icarus provides improved panel efficiency, increased power output, energy storage for power and/or hot water, and continuous grid reliability at a lower cost without the environmental downsides of Li-ion batteries.

Keywords: solar, thermal, energy storage, pv cells, organic rankine cycle

1 SUMMARY

Current photovoltaic (PV) panels have a typical peak efficiency rating of only about 21% in converting the solar energy striking each panel into electric power. As panels heat up in the sun, yield can drop to as low as 16% during the peak temperatures.

Another challenge with solar is the inherent intermittent availability (i.e., daylight hours) and the lack of energy storage. As of 2018, estimates show that 96% of PV installed systems in the United States lack energy storage, creating grid reliability problems such as the California “Duck Curve” [1]. The California “Duck” Curve illustrates that solar energy production decreases in the afternoon as demand increases, straining energy resources and the grid. Compounding the problem is the high cost of lithium-ion batteries which make solar plus storage cost prohibitive for some. Thus, consumers purchase PV systems without storage, exacerbating the Duck Curve.

Hybrid solar photovoltaic/thermal (PV/T) solar plus storage cogeneration systems are an option. At least one new system uses a proprietary heat extractor that cools PV panels to increase power yield. The heat extractors remove waste heat from PV panels and can collect and store the heat in a thermal energy storage tank. Stored energy is used to heat water or power on-demand using an ORC, reducing peak demand utility charges for customers. A control system is required to measure customer demand, solar resources, and utility rate structures to make buy/sell/store energy decisions to optimize the system and accelerate return-on-investment (ROI).

A proof-of-concept prototype demonstrates that hybrid PV/T solar plus storage systems are a viable, lower-cost alternative to traditional battery systems for reducing burden on the grid during peak demand and minimizing the energy “Duck Curve.” Li-ion battery systems are capital intensive, have high replacement costs and present significant environmental challenges. PV/T solar plus storage systems avoids these drawbacks, making clean energy storage affordable. Projections indicate that the prototype system will lower the levelized cost of energy from $0.067/kWh to $0.034/kWh when compared to current state of the art PV plus battery storage systems. A primary factor for the cost reduction is that PV/T systems boost PV array daytime output while charging the thermal battery without consuming PV production. Traditional battery systems consume PV output to charge, reducing the power available during the day.

2 BACKGROUND

2.1 Energy Storage Technology

The mismatch between daily solar power output and peak utility power demand periods has raised the demand for grid energy storage, spurring an advancement in several technologies. These systems store electrical energy when electricity is cheap and release to the grid when electrical demand is high and expensive. The most common type of energy storage is pumped hydropower but for solar power application, electrochemical batteries and thermal storage are the leading storage technologies and will be the focus of this section.

2.1.1 Electrochemical Batteries

The energy industry has seen growth in electrochemical batteries with lithium-ion (Li-ion) batteries being the most common in solar power plants. Li-ion batteries work by having positive Li-ions carry the current within the battery from the negative to positive electrode, through an electrolyte during discharge, and back when charging. Part of the reason Li-ion batteries are popular is because lithium is highly reactive, meaning that a lot of energy can be stored in its atomic bonds.

This allows Li-ion batteries to have higher energy density than other competing chemistries. Additionally, Li-ion batteries hold their charge for longer periods of time and can handle hundreds of charge/discharge cycles.

One problem with Li-ion batteries is the cost. The cost of Li-ion storage is projected to have a price between $80/kW and $248/kWh by the year 2030 [2][3][4]. Bloomberg New Energy Finance (BNEF) reports the current cost of Li-ion storage at $137/kWh, not including installation [3]. The current price is a major improvement from the $1,100/kWh in 2010 and the price is expected to reach $100/kWh by 2023. Although the future costs of Li-ion batteries look more attractive, costs still deter residential and commercial consumers from purchasing battery storage.

Another drawback of Li-ion batteries is that they need to be charged by electricity whether it is from the installed PV array output or from the grid. If a user is interested in installing a PV array to meet their daytime demand and charge the battery at the same time, the system will have to be larger and therefore more expensive.

Finally, Li-ion batteries have an expected lifetime of 5 to 15 years. There are insufficient recycling programs in place. By 2040, 0.33-4 million metric tons of Li-ion batteries will be disposed in landfills [5]. The continued reliance on Li-ion batteries poses a sustainability challenge to solar plus storage market.

2.1.2 Thermal Storage

Thermal energy storage stores heat in a fluid and releases the heat when there is high demand for heat or electricity. Standalone PV arrays only generate electricity, therefore thermal energy storage is only suited for hybrid PV/T arrays or pure solar-thermal generation arrays. The two most common storage fluids are water in applications with temperatures below 100 °C and molten salt for applications where temperatures range between 288 and 566 °C. Since PV/T panel temperatures do not exceed 80 °C, this discussion will focus on water based thermal energy storage.

The most basic systems that water thermal storage is found paired with are solar thermal collector arrays. Solar thermal collectors heat up the fluid going through them and are ideal for water or space heating applications. In a solar collector system that generates more hot water than is used by the users, a storage tank is ideal to store excess heat and allow users to use the stored energy at later time. This storage system reduces utility costs along with users demand for water or space heating.

Single-tank thermocline systems are a more sophisticated storage tank system. This vertical storage system relies on the natural stratification properties of water mixing at different temperatures. While charging the storage tank, hot fluid is added to the top and moves the thermocline downward, minimizing the cold fluid at the bottom. During the discharge, thermal energy is removed from the top of the tank, the thermocline moves upward and the amount of cold fluid increases.

2.2 California Electrification

Since January 1, 2020, California Assembly Bill 178 requires rooftop solar photovoltaic systems to be equipped on all new homes built. Additionally, at least 49 California communities now restrict the installation of natural gas appliances, such as water heaters, in new construction. The California Energy Commission anticipates closing the door completely to natural gas in new homes beginning 2023.

By 2030, all new commercial construction must meet California's Zero Net Energy (ZNE) mandate and 50% of existing buildings must be retrofitted to ZNE [6]. Renewable portfolio standards (RPS) in California require investor owned and municipal utilities to generate 52% and 60% of their energy from renewable sources by 2027 and 2030, respectively [7]. These energy mandates in California are opening a large market opportunity for innovative solar plus storage technologies to fill the space left by natural gas water heaters. States such as Hawaii, New Mexico, New York, Virginia, and Washington have established aggressive RPS goals between 2040 and 2050, creating opportunities for PV/T across the U.S. as well [7].

3. OVERVIEW OF HYBRID PV/T

New technologies are opening the door for this cogeneration system to become a reality. The subject system uses new materials (i.e., nano-coatings, low GWP organic fluids), a breakthrough heat extractor and fabrication techniques (i.e., 3D-printing) and a proprietary smart control system that were not available 5-10 years ago. These advances enable a low-cost system that substantially outperforms previous hybrid PV/T attempts.

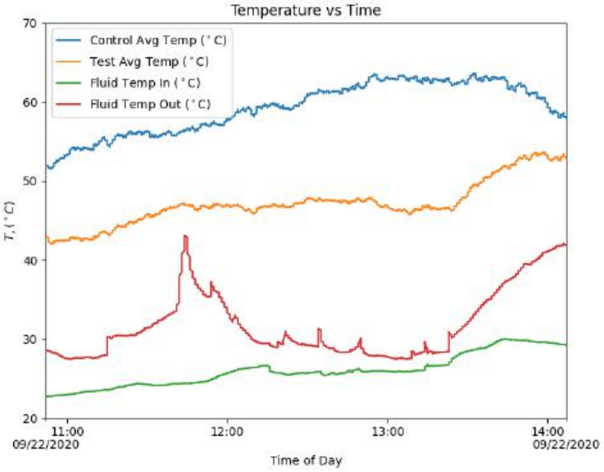

Figure 1: Heat Extractor cooling vs. Standard Panel.

Heat extractors attach to the back of standard PV panels to lower panel temperature, improve their efficiency, and heat the fluid flowing through the extractor. In *Fig. 1*, the reader can see the temperature comparison between a regular PV panel and a PV panel with a heat extractor attached. This test demonstrated the potential for heat extractors to reduce PV panel surface temperature by 12°C on average compared to a standalone PV panel. In some instances, the maximum average panel surface temperature difference between the control and the test panel was 18 °C which can increase power output by 12% (some individual cells recorded surface temperature differences of up to 26 °C at different instances which can be a 14.5% increase in power output). The temperature a panel is cooled to differs temperatures as flow continues across the extractor, absorbed heat increases the temperature of the fluid and lowers heat extraction (see *Fig. 2*). A 12°C temperature reduction produces an average fluid temperature gain of 5.7 °C between the inlet and outlet streams. The maximum fluid temperature gain corresponded to slower flow speeds and less panel cooling.

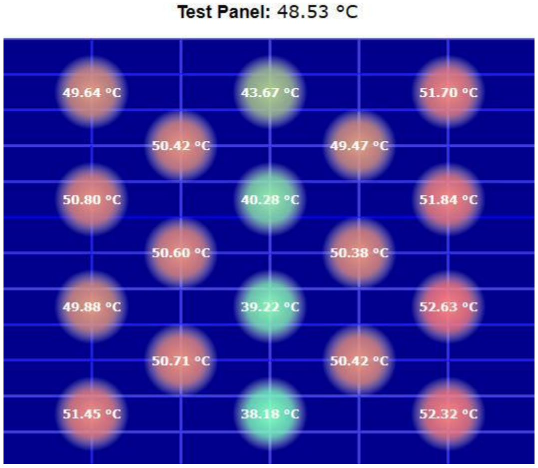

Figure 2: Image of Panel Test with Small Extractor.[1]

Control systems must be optimized to balance panel cooling and water heating to maximize power output. Additionally, optimizing the heat exchanger design with new fabrication techniques can improve panel cooling and heat collection.

Storage tank testing demonstrates that our 300-gallon insulated tank stores 23 kWh of energy with a thermocline stratification from 50 °C to 30 °C. For a 2.5-kW array, this is equivalent to 200% increase of available power (11.1 kWh) without storage (based on NREL's PV Watts Calculator). Further experiments show that the top level of the storage tank loses about 6°C (12%) over a period of 14 hours.

During testing of the 300-gallon thermal storage tank, thermal stratification stored a maximum of 18-kWh of energy, demonstrating the viability of the thermal energy battery (see Fig. 3). After 14 hours, without any energy added or removed, the energy stored in the tank was reduced to 15-kWh, demonstrating the potential for the system to store energy for on-demand use over a 12-hour period. Thermal stratification will be optimized to meet hot water demand during evening and nighttime.

The subject hybrid system has a proprietary monitoring and control system to measure performance of the heat extraction, storage and energy generation sub-systems as well as PV panel performance. Current testing of the system uses performance data to calibrate computer models that optimize and control the system based on the energy demands of the end user. These measurements are synthesized with customer guidelines and utility rate structures to make buy/sell/store decisions and to automate the actions necessary to carry out these decisions. The amount of power and hot water generated will be analyzed to estimate the cost benefit of the Quartet system, determine the emission reduction benefits, and estimate the pay-back period.

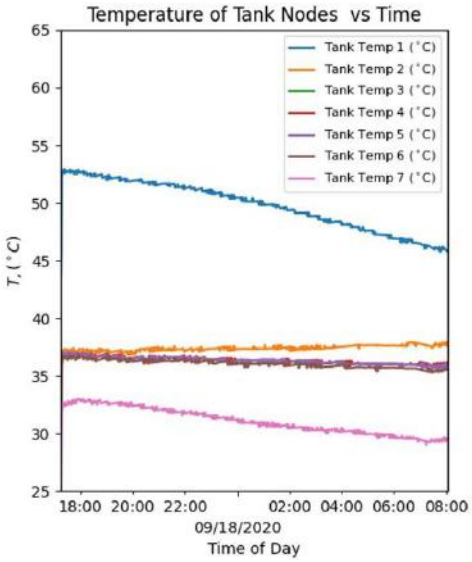

Figure 3: Energy Storage Stratification Performance.

Target performance metrics for the subject hybrid PV/T system estimate an average power output increase of at least 12%. In a 100-kW system located in San Diego, this amounts to an additional 19,000 kWh generated annually with a value of $7,400 from improved efficiency alone. Additional quantitative benefits of this project include peak load reduction, as the hot water generated can be utilized during peak evening hours in place of electric water heaters. UCI estimates that an average household uses natural gas to use 11.7 MWh annually for hot water [8]. This proposed project would provide 190 MWh/year in hot water, enough to fully supply 16 households for the year. According to the EPA's conversion factor of 700 T CO_2e/kWh, this system would prevent 147 MT of CO2e per year from entering the environment, save consumers $81,543/year (SDG&E Peak Demand Prices) in electric power and natural gas utility charges, and reduce the social costs of carbon by $6,174 per year. Social costs of carbon refer to a comprehensive estimate of climate change damage which is estimated to be about $42/MT CO_2e by the EPA.

Combining PV/T and ORC to generate power on-demand is on the horizon. The ORC will be charged with DR-14a which is a novel azeotropic blend, provided for this test by The Chemours Company, with a global warming potential (GWP)

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value of 415 (R134a has a GWP of 1410). The testing will measure PV surface temperature, PV power generated, PV/T outlet temperatures, solar collector outlet temperatures, storage tank temperatures, storage tank energy, ORC power, ORC energy generated, and thermal efficiency between the storage tank and the ORC. These data values will be collected through temperature, flow, pressure, and electrical sensors that are included in the system design.

4 CONCLUSION

In addition to helping California meet its statutory energy goals, PV/T solar plus storage cogeneration technology like the example discussed will also benefit ratepayers by improving grid reliability. PV/T systems can apply these same positive results throughout the US and World. Grid reliability will improve as energy storage systems transition daytime solar thermal energy smoothly to meet hot water on-demand thus reducing demand on natural gas for power plants and water heaters. PV panel lifetime, and lifetime performance improve as a result of lessened heat cycles, and heat fatigue.

PV/T technology is poised to become a vital component in the next generation of solar projects by providing a cost-effective and environmentally responsible alternative to traditional batteries. The PV efficiency improvement and solar thermal collection enables lowered costs of generation and an accelerated ROI without a large increase in area required for solar installations. Although PV panels can be very effectively retrofitted with PV/T, the attachment would be even more effective if included in the PV manufacturing process as the base of the panel for PV modules to be assembled upon. In the future, the inclusion of PV/T heat extractors in the fabrication of PV panels may increase heat transfer and reduce cost.

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