Beyond the grid: the promise of solar concentration for non-electrical energy production

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ABSTRACT

As electricity from both photovoltaics and concentrating solar power has become dramatically more affordable in the last several years, the prospect of converting entire national electrical grids to run almost entirely on renewable energy has become feasible in any location with a strong solar resource. However, focusing only on the electric grid neglects the large portion of our energy usage which is thermal rather than electrical. One frequently proposed solution has been to simply electrify all thermal processes, for example in heavy industry, space and water heating. We suggest that the direct use of solar heat for thermal processes enables savings in terms of energy loss, land usage and dollar cost. Focusing on the requirements of heavy industry, desalination and long-distance heat transport, we identify the current and future potential of efficient collection, use and distribution of solar heat to extend the ongoing renewable revolution beyond the grid.

Keywords: Process heat, desalination, solar concentration, thermal energy storage, solar thermal power

1. INTRODUCTION

As the need to decarbonize the world's energy systems becomes increasingly evident, renewable energy, in particular wind and solar, has proven itself a cost-effective way to meet this need [1,2,3]. Due to outdated perceptions of their economics, the fact that solar and wind power are now cheap, compared with fossil fuel generation, over a large part of the world, is often overlooked in policy discussions. However, as a combination of industrial learning [4] and fortunate happenstance [5] have combined to dramatically reduce the cost of solar panels, and growing confidence of governments and the financial sector has allowed large amounts of capital to be raised at low cost [6], the price of solar electricity has fallen to below-market levels across much of the world [7]. A similar story has unfolded with wind energy [8], and as a result much of the world now has access to low-cost, large scale renewable energy as an option for decarbonizing their electric grids. To account for the intermittency of these sources, concentrating solar power with thermal energy storage (CSP+TES) has risen in high-insolation areas as a critical player in balancing the electric grid. A recently ordered 950MW combined PV+CSP project in Dubai illustrates the power of this combination [9]. Nighttime demand will be covered by the thermal component, using stored solar thermal energy, at a power purchase agreement (PPA) price of 7.3 ¢/kWh. The PV component has no storage and will sell electricity during the day only, for 2.4¢/kWh. Taken together, these prices indicate an overall levelized cost for 24-hour solar electricity of 5-6¢/kWh. Combining these fundamental generation technologies with the rise of electric vehicles and their enabling technology, reliable battery storage, it seems that a reduction of 80-90% in the carbon intensity of both the electric and transportation sectors simply requires political will and the marshalling of sufficient capital for investment.

At the time of this writing, the world is approaching its first terawatt of installed solar capacity, and generated just over 500 terawatt-hours of electricity in 2018 [10]. However, electricity use in the US alone accounts for roughly 4 petawatt-hours, and the entire primary energy consumption of the United States is 25 petawatt-hours per annum. In other words, if the United States wanted to reduce its overall GHG emissions from energy production by 80% by 2030 – a goal which is technologically feasible as will be illustrated in this manuscript – by fully converting its economy to run on renewable electricity, we would need to install, per year, more than twice the amount of solar generating capacity that currently exists in the world.

Given these daunting numbers it makes sense to seek, whenever possible, ways to more efficiently use solar energy in order to reduce the amount of solar generating capacity that is needed. The wide array of solar thermal technologies now available, informed by experience from around the world, present a set of previously underappreciated options for the direct utilization of solar heat for a wide range of applications.

2. ENERGY CONSUMPTION, EMISSION SOURCES AND THE ROLE OF THERMAL ENERGY

According to the EPA [11], global greenhouse gas (GHG) emissions can be broken down as 25% from electricity generation, 24% from agriculture and forestry, 21% from industry, 14% from transportation, 6% from buildings, and 10% from other sources. Emissions from electricity generation could be eroded by maintaining existing nuclear and hydropower capacity in the medium-term while phasing out first coal, and then natural gas, for a combination of PV, wind, CSP and an array of energy storage options. Ground transportation is moving towards electrification with the rise of electric vehicles, which will remove most emissions from this sector if the added electricity demand can be supplied from carbon-neutral sources. Emissions from agriculture include many aspects of which powering machinery is a part; electrification of the agricultural sector or even turning it into a net energy producer will depend on finding solutions for simultaneously using land for food and power production [12]. Building consumption does not include purchased electricity and is primarily combustion for heating and cooking. Electrification is one pathway to reduce emissions in this sector but there may be other options, which will be explored here.

Industry – over one-fifth of global emissions – represents a key missing piece of the puzzle. Electrification of industrial processes has been proposed as a means to convert this sector to run on renewable or carbon-free energy. However, a closer look reveals a challenge to this approach. In the United States, process heat accounts for roughly two-thirds of industrial energy consumption [13]. Nearly all of this is generated by combustion. A simple calculation illustrates the challenges that would be entailed in replacing combustion with electricity as a source of heat.

First we consider that the economic requirements of heavy industry to maximize production, and the physical constraint that expensive infrastructure should not be cycled daily between ambient and very high temperatures to avoid thermal stress and wear, conflict with the intermittent nature of cheap photovoltaic systems, necessitating large amounts of electrical energy storage capacity or CSP+TES. Energetically, the drawback of such a scenario is clear if we consider electricity generated by CSP. A plant with a turbine efficiency of 33% will consume 3x more energy in heat than it releases in electricity. However, the largest use of energy in industry is the generation of process heat – either by combustion or in electrical machinery. Therefore, the intermediate step of producing electricity destroys most of the thermal resource that has already been collected from the sun. Providing process heat for a given facility – thinking purely in MWh thermal delivered – using CSP requires a collector array and thermal storage block roughly three times larger than what would be required if solar heat were used directly. Furthermore, the power block represents roughly one-quarter of current CSP+TES capital costs, based on market studies and financial figures from recent projects. If we start from a figure of USD 6 billion per GW_e of CSP+TES capacity – derived from the reported costs of the UAE's recent project [9] – this leads to a figure of USD 1.5bn/GW_t of solar heat capacity. This is approaching the cost of photovoltaic capacity without energy storage (~$1bn/$GW_e$) – but consuming roughly one-third the land area and with built-in energy storage capacity. If we consider the levelized cost of energy (LCOE) the economics become even more favorable. Starting from the figure of 7.3 ¢/kWh_e offered for CSP+TES in Dubai, and assuming that financing rates remain constant and operating costs scale with plant size, this gives a figure of less than 2¢/kWh_t for *nighttime* solar heat – below even the record-low costs for nondispatchable PV electricity. Taking this perspective, the problem seems to be a no-brainer – in terms of energetics, capital cost or land use requirements, any thermal process that can directly use solar heat should do so, rather than electrifying, unless the electrical process can improve efficiency by 3-4 times relative to current processes, while maintaining current costs of machinery.

3. TEMERATURE REQUIREMENTS FOR PROCESS HEAT: MATERIAL CHALLENGES AND ENGINEERING SOLUTIONS

Industrial process heat encompasses a wide range of processes requiring different temperatures. In Germany, for example, roughly one-third of process heat is <400°C, of which the majority is 200°C or less. One-third is for high-temperature processes (>1000°C) such as metalworking, with one-third in the intermediate range [14].

A range of solar technologies are available to serve these different temperature ranges. Flat-plate collectors can satisfy the low-temperature range of ~100°C; low-concentration devices such as the compound parabolic concentrator (CPC)

[15] can service the 100-200°C range. In conventional parabolic trough collectors, the temperatures that can be achieved with solar heat are limited to 350-380°C due to the limitations of heat transfer oil. Central receiver systems using molten salt as a heat transfer fluid can reach temperatures above 500°C. Options for high temperature include direct steam generation and solar furnaces. When the heat tolerance of thermal transfer media is exceeded, however, storage and extraction of thermal energy becomes challenges. Therefore there is already a need for continued development of practical heat transfer media with high temperature tolerance.

Based on this, roughly one-third of industrial processes could be fully powered by solar heat from established, modular technologies (flat-plate receivers and troughs). If molten-salt systems are used reaching temperatures of 550°C, this figure approaches one-half. One counterintuitive example where solar heat is already finding application is the in the oil industry of Oman. The industry is a major user of steam for enhanced oil recovery, and generates its steam by burning natural gas. The Miraah solar-thermal project is anticipated to replace 5.6 trillion BTU of natural gas annually (which would avoid 300,000 tons of CO_2) by using a 1GW parabolic trough field to generate steam from solar heat [16]. If successful this project could serve as a model for other industries on how to convert combustion-powered operations to run on solar energy.

The applications of solar heat are not limited to processes that do not exceed the temperature tolerance of heat-transfer media. An example of how this temperature limit could be exceeded is observed in the Shams 1 CSP plant in the western desert of Abu Dhabi [17]. To boost the turbine efficiency (which is degraded by the use of a dry cooling system than increases the condensation temperature of outlet steam), the plant combines a solar field of parabolic troughs using a heat transfer oil to heat steam to 380°C, with a gas-fired burner providing additional heating to 540°C. This approach can also be applied to industrial process heating, where solar energy can provide heating up to 380-550°C, depending on the concentrator technology and the choice of heat transfer fluid, with subsequent heating supplied by combustion. In this way solar heat could in principle displace the majority of CO_2 emissions from industrial process heating using current technology. The hybrid approach may prove valuable as a way to avoid large one-time capital investments, by gradually expanding solar heating capacity to displace fuels over time. Further displacement can be achieved as improvements in technology, particularly the development of high-temperature heat transfer fluids, enable higher-temperature heat to be generated and stored in solar facilities.

At the other end of the temperature scale, the experience of the Middle East suggests another use for low-grade solar heat that will become increasingly relevant in a warming world with inconsistent rainfall patterns. The region is home to the world's driest countries which depend heavily on desalination for their water needs. Despite the global trend towards reverse osmosis, the Middle East relies heavily on thermal desalination. With the region's large hydrocarbon resources, heat has historically come essentially for free as a byproduct of thermal electricity generation. In the Gulf, the demand for desalination is so great that waste heat from power plants is insufficient to meet it, and hot steam is instead bled from the turbines to provide a larger thermal resource for desalination, sacrificing some electricity production in favor of water production. Hence electricity and water are generated together at the same facility, typically owned by a combined water-electric utility. This paradigm of combined electricity and water production appears to be threatened by the shift to photovoltaics to provide a large portion of electricity. However, this is not fundamentally necessary as photovoltaic electricity generation is also a thermal process, where the combination of thermalization and below-bandgap absorption in a commercial solar cell typically produce 3-4 times more heat than electricity. The concept of combining low-concentration CPV with waste heat recover from solar cells has a long history. In combining solar electricity generation with thermal desalination in coastal desert regions, it may finally have found a large-scale application. As the temperature requirements of thermal desalination are typically about 70°C, heat can be recovered at the required temperature without excessively reducing the efficiency of the cells, relative to normal operating conditions in the region. An alternative could be to extract heat at a lower temperature and then use heat pumps to boost the temperature to the required levels. This concept will require optimization both in terms of total useful energy produced, and in terms of system costs and lifespan.

The transition towards solar heat raises another significant question: how do we account for the fact that the strongest solar resource as typically in inland areas, but the applications for solar heat – either industry, which is preferable to locate near ports, or desalination – are typically located near the coast? If solar heat is to play leading role in future industry, it may prove advantageous to make significant investments in infrastructure to transport heat from where it can be most efficiently collected to its point of use. Transport of thermal energy, at least at low temperatures, is a problem with which there is significant experience, thanks to the long history of district heating networks in cities around the world. A particularly extensive example is the district heating system of the greater Copenhagen area, in which several dozen power plants, waste incinerators and electric boilers are connected to residential and commercial buildings via a network of pipelines spanning the metropolitan area [18]. In the case of lower temperature applications, including desalination, the experience of district heating likely provides all that is needed to assemble the required infrastructure.

4. CONCLUSION

In the quest to decarbonize the world's energy systems, industry represents a missing piece of the puzzle where the current low-cost technologies, photovoltaics and wind turbines, are not ideal for meeting energy demand. Due to the heavy dependence on process heat across industries, we anticipate that solar thermal energy will play an outsized role in the decarbonization of industry. While the adoption of solar heat remains challenging for some high-temperature processes, existing solar thermal technology can in principle provide the majority of the thermal energy required for industrial processes. As additional high-energy sectors grow – with desalination expected to make a large contribution – continuing to develop technologies and infrastructure to more effectively collect, transport and use solar heat will play a critical role in decarbonization.

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