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THE BGU/CERN SOLAR HYDROTHERMAL REACTOR

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Abstract

We describe a novel solar hydrothermal reactor (SHR) under development by Ben Gurion University (BGU) and the European Organization for Nuclear Research CERN. We describe in broad terms the several novel aspects of the device and, by extension, of the niche it occupies: in particular, enabling direct off-grid conversion of a range of organic feedstocks to sterile useable (solid, liquid) fuels, nutrients, products using only solar energy and water. We then provide a brief description of the high temperature high efficiency panels that provide process heat to the hydrothermal reactor, and review the basics of hydrothermal processes and conversion taking place in this. We conclude with a description of a simulation of the pilot system that will begin operation later this year.

Key words: hydrothermal carbonization, renewable energy, solar thermal, waste management,

1. Introduction and overview

The unique reactive and solvent properties of water heated above its usual boiling point under pressure have been known for a century, and have become of increasing interest as a means to process biomass, as well as achieve a range of reactions without the use of expensive and potentially toxic organic solvents. While some mention has been made of utilizing solar energy to drive hydrothermal processes, this has taken the form of a glancing reference to a future possibility, or else based on an implementation dependent on large and/or focusing solar collectors, which have been seen as necessary to achieve the temperatures around and above 200 C required for hydrothermal reactors. Beginning in late 2013, our respective organizations, each with an interest in translating advanced technologies into broader contexts, and especially in developing countries, have been engaged in the Solar Hydrothermal Advanced Reactor Project (SHARP), aimed at developing a pilot device consisting of a small (30-50 litre) hydrothermal reactor powered by the SRB high vacuum solar panels, which produce high temperature water at high efficiency directly from flat panel collectors. This instrument is small and robust enough to be moveable, making viable solar powered off-grid *in situ* processing of a range of feedstocks that would otherwise be wasted or even a nuisance. As described below, developing such a device in a way that greatly broadens the range of potential use cases for solar hydrothermal technologies presents an exciting socio-technical challenge.

2. Several layers of novelty and promise

While solar thermal panels and hydrothermal reactors are familiar technologies, our particular combination of these, and our effort to harness the combined device to off-grid contexts underscores several subtle but important layers of innovation. As described below, the SRB solar panels produce high temperature outputs at high efficiencies, without the need for focusing. In locations where electricity or other sources of energy are available, the production of high temperature process heat is not a striking achievement, but the ability to

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do this in remote locations is important. The hydrothermal conversion of biomass is in itself remarkable (allowing conversion of wet biomass to solid and liquid fuels and nutrients with 100% carbon efficiency), and becomes more so when it can occur in off-grid settings, without costly infrastructures and energy sources. This is because the kind of biomass most amenable to such conversion is typically widely distributed, often in rural settings, and difficult and marginally worthwhile to transport for processing. Being able to bring a reactor to the biomass, rather than the other way round, may bring within the envelope of viability a range of locations and feedstocks that would otherwise be wasted or discarded with hazard. The viability of the operation is furthered boosted by the fact that the reaction products become available in the location of potential use, not requiring packaging, transport, and resale. The promise of the solar hydrothermal combination extends beyond waste management and fuel production. In essence, the versatile range of hydrothermal reactions possible under various pressure/temperature/feedstock combinations makes possible delocalized low input processing (including specialized production and decontamination) that would otherwise require expensive and toxic reactants in a large facility.

Taking a step backwards to the big picture, we can see that, if achieved, a small off-grid solar hydrothermal reactor would constitute an important development in the utilization of solar energy. As illustrated in Figure 1, it allows captured solar energy not only to be used directly, but to be used to recreate the high temperature high pressure conditions in which fossil fuels were formed, and thereby create—but on a much briefer time scale—a fossil fuel analog (coal), which can substitute for the traditional fossil fuels.

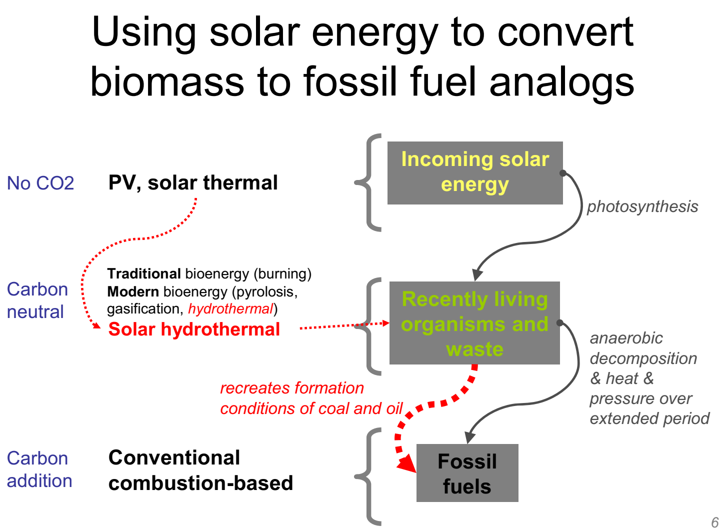
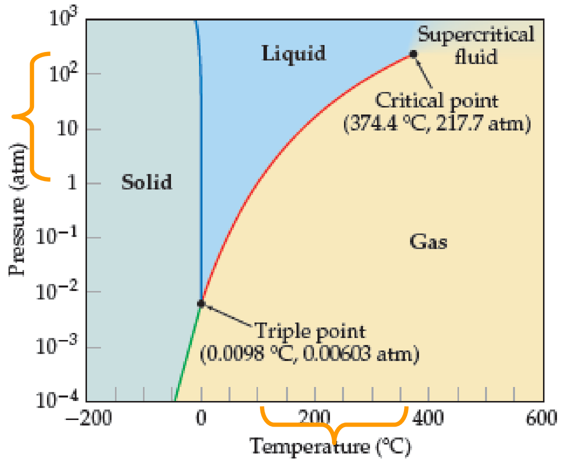


Figure 1: schematic conceptualization of solar hydrothermal within landscape of alternative energy sources

3. Hydrothermal processes and biomass conversion

The relationship between water temperature and pressure is commonly represented on a pressure-temperature (P-T) diagram, such as that of Figure 2, in which a "coexistence line" demarcates the transition point between phases at a given temperature/pressure combination. The situation most familiar to us is the behavior of water around one atmosphere, where water moves between three distinct phases.



Phase diagram of water (note logarithmic pressure scale). (Adapted from Brown 2014)

Figure 2: Phase diagram of water

The increase of system pressure brings less familiar behavior. As indicated by the red line, as pressure increases, the vaporization of liquid water is "suppressed" –it takes a higher temperature in order for the water's vapor pressure to exceed the prevailing pressure. In practical terms: we can use pressure to control the boiling point of water.

Pressurized hot water above the usual boiling point is referred to as "superheated." It is also called "subcritical water," in reference to what is called the "critical point" of water, around 374 °C and 22 MPa (218 atm.) This is the point beyond which no increase in pressure suffices to retain a liquid state at increased temperature, and no increase in temperature will vaporize the liquid at this pressure. Beyond the critical temperature, the kinetic energies of the molecules exceed the attractive forces between them now matter how much compressive force is applied. In fact, at the critical point, the distinction between the properties of gas and liquid ceases to exist, a state referred to as a "supercritical liquid" in which the molecules are closely spaced, like a liquid, but expand to fill their container, like a gas.

While most people are intuitively aware of the ability of superheated water to accelerate chemical reactions because of their familiarity with pressure cookers, which cook food more rapidly than boiling at room pressure, its many remarkable properties are less well known. Raised temperature and pressure alters the density, dialectric constant, and ion dissociation constant of water in ways that alter it from a relatively inactive polar highly hydrogen-bonded solvent to a highly active non-polar solvent of organic substances.

Three hydrothermal processing regions are commonly referred to, as indicated on the phase diagram of Figure 3.

- **Hydrothermal carbonization (HTC)** (180-280 °C) → hydro-coal (solid fuels).
- **Hydrothermal liquefaction (HTL)** (280-374 °C)→ crude oil (liquid fuels).
- **Hydrothermal gasification (HTG)** often referred to as supercritical water gasification (SCWG) (374-700 °C) →CH_4

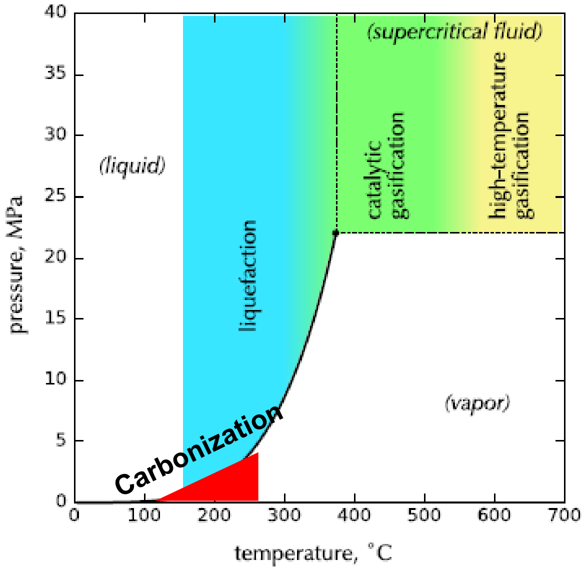


Figure 3: Regions of hydrothermal processing (after Peterson et al., 2008)

The reactor we describe here will operate primarily in the lower range of temperatures and pressure (180-280 °C, and under 5 MPa (50 atmospheres), in which processes of hydrothermal carbonization (HTC) take place, converting wet biomass into a bituminous-coal like material (HTC coal) as well as water soluble aqueous co-products useful as fertilizers, and gases (Berge, 2011; Kruse, 2013; Libra, 2011). HTC has attracted considerable attention for its potential for converting wet waste materials into a range of value added products and as a means of high efficiency carbon recovery without the process of drying required by traditional thermochemical processes (combustion, air gasification, pyrolysis). Our preliminary calculations and experiments confirm that the energy that can be produced from the product is significantly higher than the energy needed for the HTC treatment: typical wet animal waste requires 2.5 MJ/kg for treatment while producing biocoal with an energetic yield of >10 MJ.

The chains of reaction in "one pot" HTC transformation are remarkably complex, depending on the pressure, temperature, residence time (typically from 1-4 hours), moisture content of the feedstock, and, of course, the nature of the feedstock itself. The components of the feedstock cellulose, hemicellulose, starch, lignin, lipids and fats, and proteins undergo dehydration (in which hydrogen and oxygen are released from organic molecules in the form of water), Decarboxylation (which removes a carboxyl group (COOH-) and releases CO_2), and condensation–polymerization-aromatization, in which organic matter is degraded to monomers which are polymerized and aromatized to form hydro-coal (char). As opposed to alcoholic fermentation, in which two of six carbon atoms are released as CO_2, or anaerobic conversion to biogas, in which about half of the carbon is released as CO2, in the HTC process almost all of the carbon in the biomass is converted into carbonized material, with only little generation of CO_2 or CO. Thus, HTC has high carbon efficiency (Titirici et al., 2007). In this way, as with the natural formation of various coal products, the hydrogen/carbon and oxygen/carbon ratios of the material are reduced, as illustrated in the typical representation of coalification pathways in Figure 4

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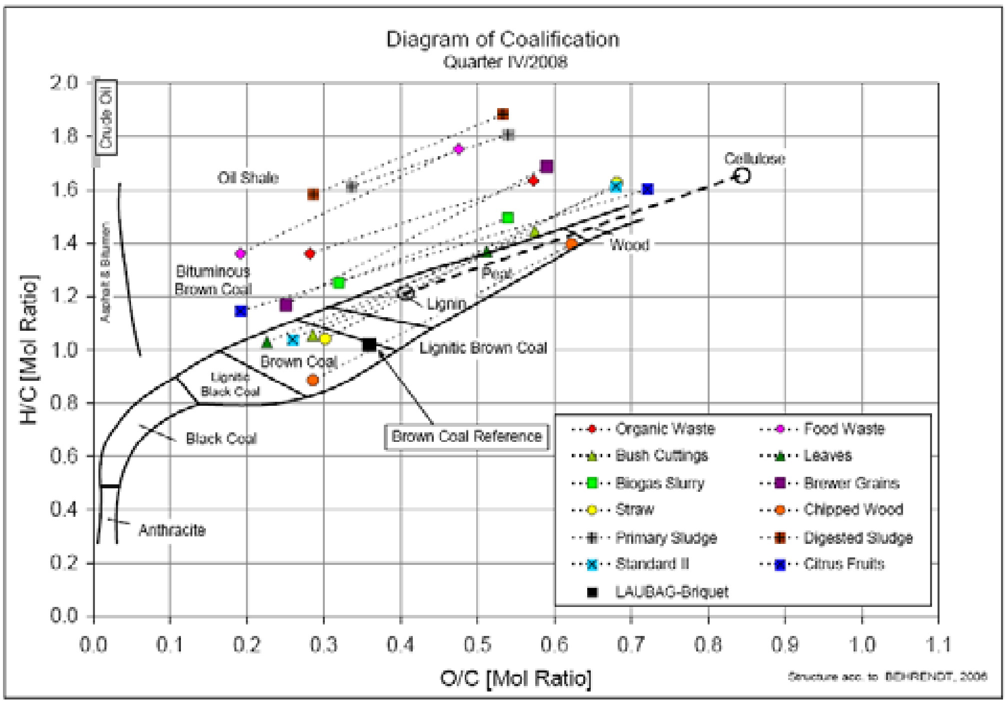

Figure 4: Diagram of coalification (from Ramke, 2009)

The high carbon efficiency of HTC is only one advantage of this approach to processing biomass over other approaches to bioenergy, such as biogas. The high temperatures destroy pathogens and breaks down many organic micropollutants (such as pharmaceuticals that may be found in animal or human waste). It can be performed with a smaller reactor and faster reaction times. It produces comparatively fewer greenhouse gases and odors. I allows the production of solid fuels, and, also, more effective recovery of nutrients (N-P-K). The inputs to HTC can be organic components of municipal solid waste, commercial wastes (from dairies, slaughterhouses, or canteens, for example), wastes from food and crop processing industries and agricultural residues themselves (including animal manures), and residues from forestry (Ramke, 2009). The emphasis of HTC can be as a waste management approach with valuable byproducts, or as energy generation approach in its own right. The optimal kind of HTC processing infrastructure and pathways for a given context will depend on this emphasis, on the feedstock and desired product, and on a large range of considerations related to the transport, availability, and other considerations (Libra,).

4. The SRB high temperature/efficiency panels

Solar energy has, by large, not been considered as an energy source for hydrothermal reactors because of the common perception that only concentrating solar collectors can yield the high temperatures needed. In our project, however, we use another approach to producing high temperatures, namely through utilizing non-focusing (flat plate) collectors, in which heat losses are minimized by reducing not only radiation losses of the collector surface, but also thermal losses from gas conduction/convection and mechanical contact (SRB, 2014). An additional gain in this non focusing approach is possible since it allows gathering the energy of diffuse light, which is around 30% in even sunny climates, and can be as high as 50% in central European settings. The collector panels are shown in Figure 5.

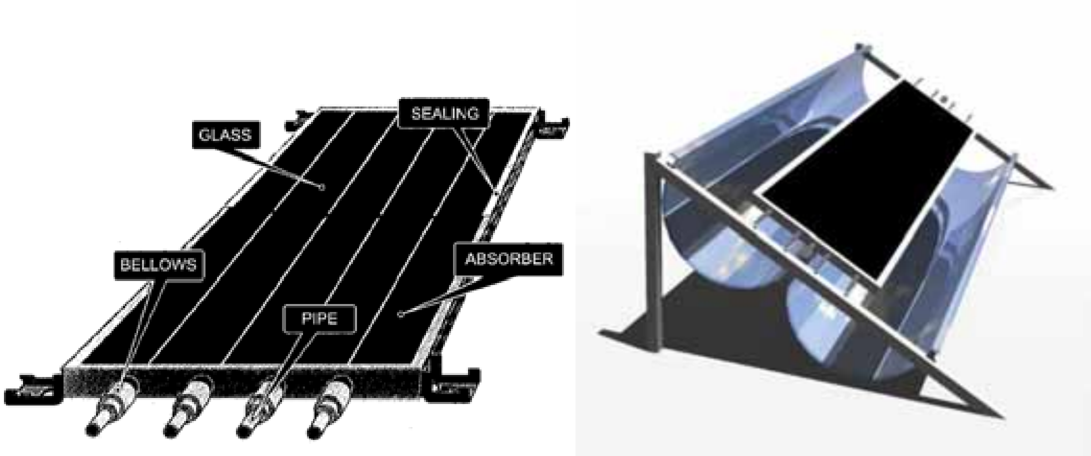

Figure 5: SRB Energy solar thermal collector (left) and its assembly in a standalone structure with cylindrical mirrors (SRB Energy C1 collector).

The absorbers are fairly standard: copper heat absorbers are electrolytically coated with black Cr oxide, with selective optical characteristics (absorption coefficient of about 0.9 and infrared emissivity of below 0.07 at 300 °C.), laser welded to stainless steel pipes that allow heat to be extracted by a circulating fluid. The distinctive aspect of these collectors, which enables their exceptionally high performance and higher output temperatures, is the maintenance of ultra high vacuum inside the panel over a 30 year panel life. By evacuating the panel, thermal losses are reduced dramatically compared to traditional solar panels, and panel temperature is limited only by emission losses through infrared radiation. The vacuum technologies employed in the panels were originally developed at CERN for use in particle accelerators, and then adapted by SRB Geneva for solar panels, which are now produced commercially by SRB Spain (SRB, 2014; Benvenuti 2010; Benvenuti, 2013). The key vacuum technologies that allow these panels to maintain a vacuum of (10^{-4} Torr) over the 20 + years of their lifetime are the following.

- A vacuum-tight connection between the large glass windows and the metal structure, enabled by a plasma-sprayed metal coating on the glass perimeter, onto which the metal joint is fixed by soft soldering
- A non evaporable getter (NEG) pump that consists of a metallic alloy coating that maintains the vacuum by "soaking up" residual gas molecules in the evacuated panel space by bonding with them. As the getter surface become gradually saturated, it is "cleaned" by heating in the normal course of panel operation, which diffuses the trapped molecules from the surface into the bulk of the getter mass.
- A mechanical structure consisting of longitudinal supports, spaced at 14 cm to prevent implosion of the panel windows due to the atmospheric force of $10N/cm^{-2}$

Heat is transferred from the collectors to industrial processes, such as the hydrothermal rector, described below, through heated oil pumped through the collectors (the pumps can also be operated using solar energy). The panels provide a temperature of above 300 C without focusing mirrors, and with the addition of simple cylindrical (nonfocusing) mirrors that capture both direct and diffuse light, temperatures above 400 C can be achieved. A prominent installation of these panels on the roof of the Geneva airport with an aperature area of 1139 m^2 produces 530kW at 130 °C, or an annual solar yield of 566 MWh. As is evident from Figure 6, the thermal efficiency remains high at the necessary operating temperatures, especially in the high irradiance areas of the pilot installation at Sde Boker, Israel.

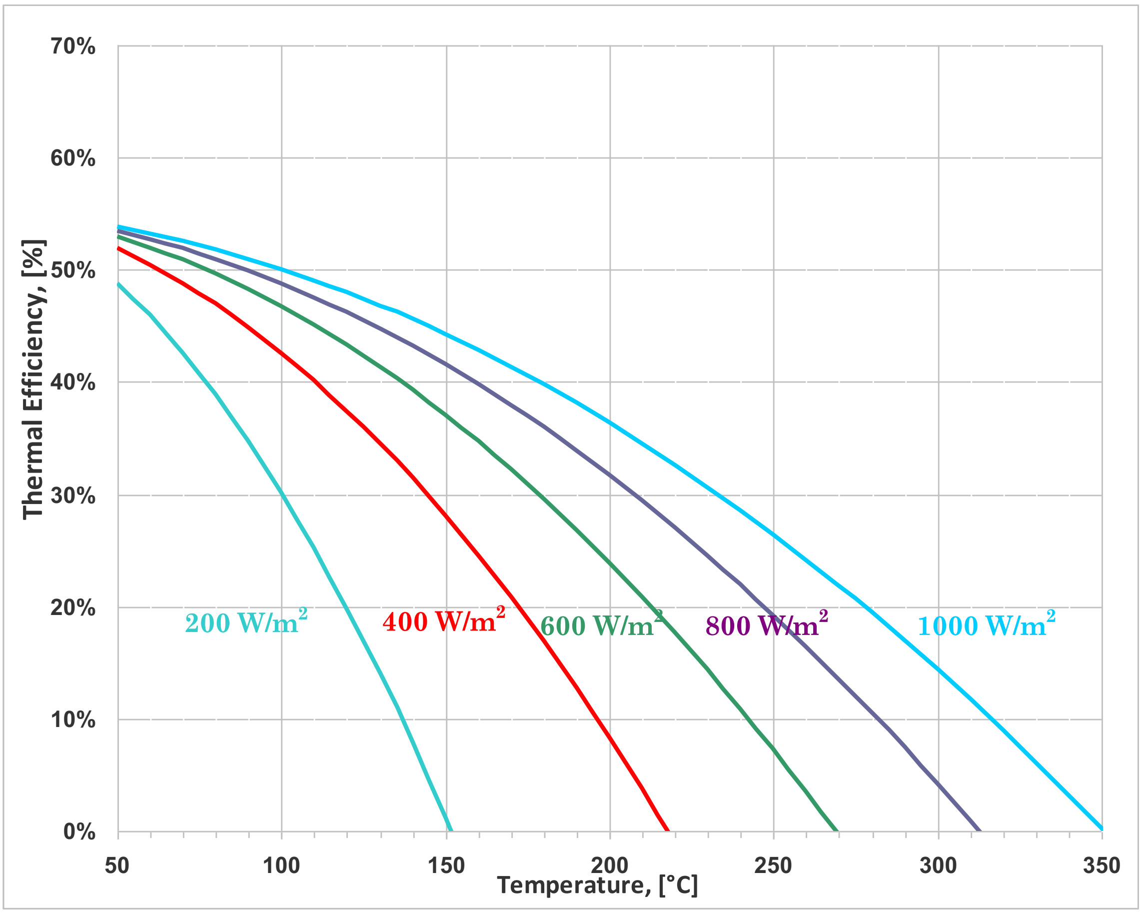

Figure 6: Thermal efficiencies as function of temperature

5. The joint solar hydrothermal system: description and results of initial simulation

Our pilot facility consists of four SRB panels (of 4 M^2 each), and one 30 litre reactor, arranged in an optimized configuration. To perform the simulations presented in the following paragraphs, it is assumed that four collector are installed as depicted in Figure 7, in a single meander circuit.

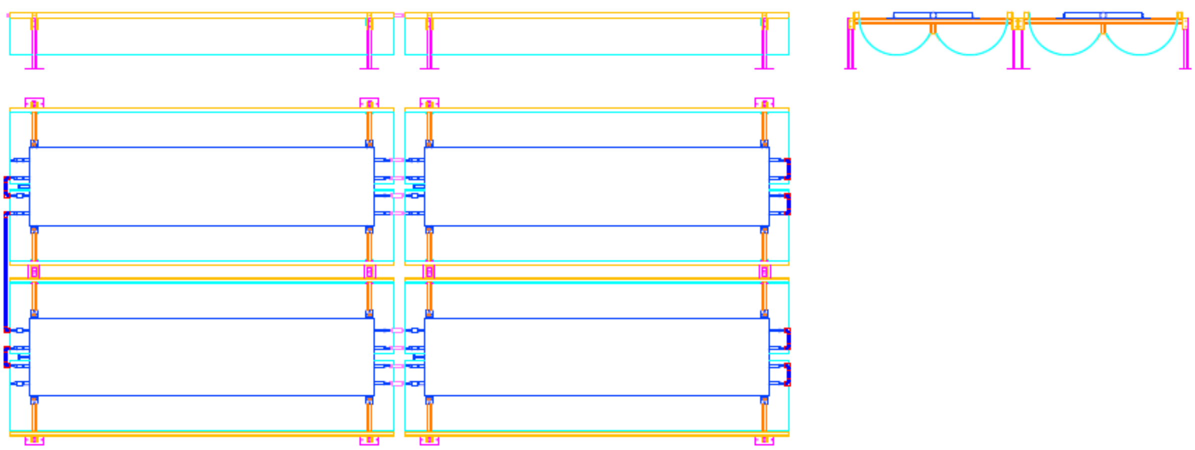

Figure 7: Solar collector field made of four SRB Energy C1 collectors connected in series in a unique meander circuit.

Both panels array and reactor are equipped with sensors and dataloggers, as well as the necessary equipment for circulation of heating fluid, etc. Prior to installation, a simulation of the system was performed (Pauletta, 2014), based on the specifications of the equipment and solar insolation at the pilot site at the Sde Boker campus of Ben Gurion University, with daily performance and temperature profile based on heat exchange modeling and integral approach energy computations.

Under the assumption of water in a liquid phase throughout the process, at 40 bar, about 12.5kWh are needed to heat the vessel and its 30 litre content from 20 °C to 250 °C (i.e., total heat capacity of 195.5 kJ/K). Using measured solar data for a sample year, the irradiance, collector temperature and reactor tank temperature over the course of full days in each of the four seasons are shown in Figure 8, and the mean collector field efficiencies, which are between 30-38%, are shown in Table 1.

Period	Efficiency	unit
From December to February	30.0	%
From March to May	34.5	%
From June to August	37.9	%
From September to November	37.8	%

Table 1: Mean collector field efficiency between 20 and 250 °C assumed during annual performance calculation derived from dynamic daily simulations during typical days in SdeBoker.

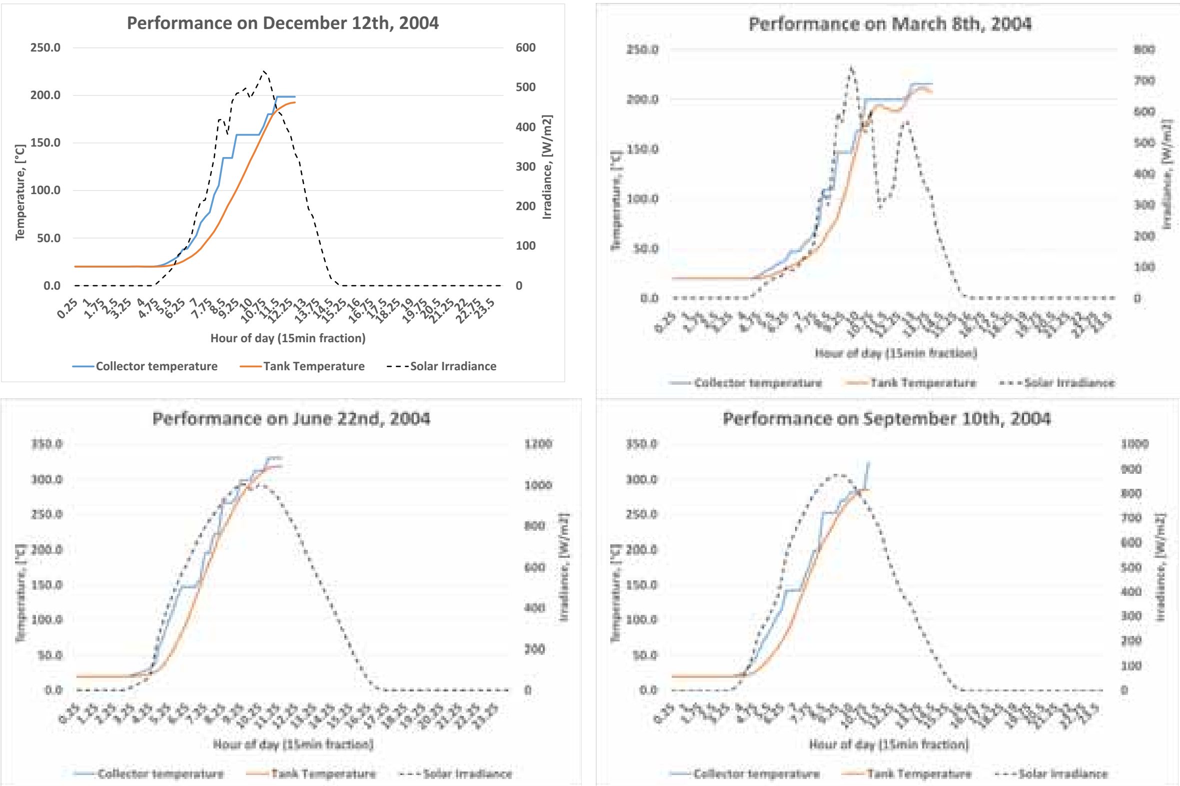

Figure 8: Simulation results of the thermal performance of 4 SRB Energy C1 collectors installed horizontally in SdeBoker, showing the collector and tank temperatures together with the solar irradiance during four representative days of the year. The collector temperature profile features stepped increase due to the adopted approximations and to the transition of oil flow from laminar to fully turbulent regime.

A key figure for the economic analysis of the device is the number of batches that can be done over the course of the year. This was modelled under three separate scenarios. The first is of no heat recovery: after a batch is complete, all remaining heat is discarded, which means that any subsequent batches can be made on the remainder of the same day only if the solar energy suffices for a full heating cycle. The second scenario assumes that 50% of energy from one day can be carried over to the next. And the third assumes not only this energetic carry-over from day to day, but, also, that energy recovery (of 50%) between batches is achieved through the use of a second reactor, so that surplus heat from a first batch can pre-heat a second. The simulation shows that 700 batches can be processed annually with no recovery, 797 batches under the daily carry-over, and 1063 batches can be processed with both forms of energy recovery taking place. As is shown in Figure 9, daily batches can be prepared throughout the year, with four or more batches possible during the summer months.

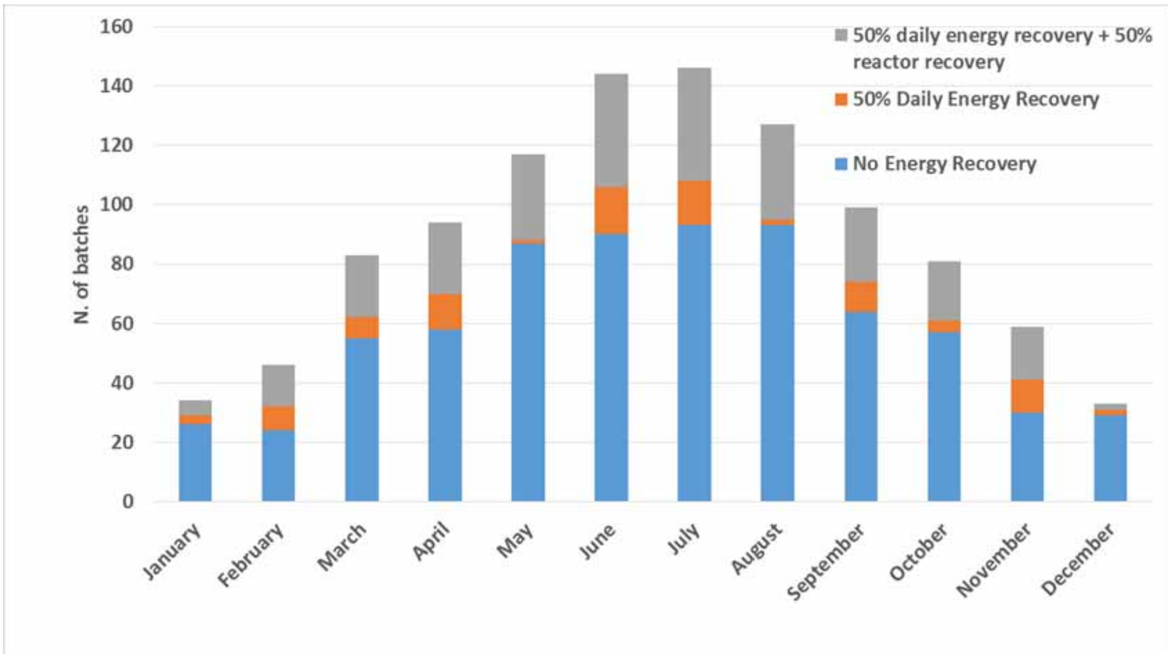

Figure 9: HTC batches per month under different energy recovery scenarios

Toward the end of 2014, with the pilot installation operating, our work will focus on characterizing the system in a variety of ways. These include the following.

- **Inputs**: feedstock; optimization of water %
- **Biochemical reactions** and their shaping by controlling factors and treatment time
- **Outputs**: their mass & energetic / nutritive value
- **Safety and convenience** of operation
- **Transportability** of device
- **Energetics** of operation
- **Economic feasibility**

6. The broader contexts of practical and economic feasibility

Biocoal is a carbon-rich, energy dense, porous and sterilized value-added product that can be used as a solid fuel for bioenergy applications, and it can also be directed to other uses such as adsorbent or permeable reactive barrier, nanostructure carbon material, a carbon catalyst for use in production of fine chemicals, etc. The liquid outputs of the HTC reactor can be used in agricultural contexts for their nutrient value. Additionally, since hot-compressed water is highly reactive, the reactor sterilizes pathogens, and breaks down many pharmaceuticals, pesticides, and industrial chemicals, which are possibly present in biowaste (Weiner, 2013). This makes the process additionally attractive for treating animal and human wastes. In some use scenarios, the waste management function of the reactor will be foremost, allowing relatively cheap and convenient disposal of troublesome or hazardous biomass, with energy and nutrients as a useful byproduct. In other scenarios energy production will dominate, and in others some specialized reaction process (to produce specialized products or perform decontamination, for example).

The novelty of our reactor is the fact that it uses solar energy as the sole energy input, and it is small enough to be transported and operated in off-grid locations. This drastically changes the overall feasibility and use analysis of the technology. Most existing economic evaluations are based on assumptions that are not relevant to our case, including a large capital cost (hundreds of thousands of dollars) for the reactor, and significant costs for energy inputs as well as for the transport of biomass inputs and reaction products over long distances. A typical use scenario for our reactor would assess the payback time for a reactor costing an order of magnitude less than this, operating *in situ* on something like 100 liters of biomass a day, using only solar energy to produce value from the removal of waste as well as energy products (20-30 kg of HTC coal, with a caloric value of 27 MJ/kg), as well as nutrients, both of which may be able to be used relatively locally. Our characterization of feasibility, therefore, includes assessment of the kinds of feedstocks and contexts in which such an arrangement is viable; the role of and means to device moveability (or, even, portability), to service geographic areas on an as-needed or rotating schedule; and assessments of how much the device cost can be brought down under conditions of mass production of panels and reactor for the end use of a robust system dedicated to solar hydrothermal production in a developing country context. We do not know the answers to these questions, and welcome the insights and suggestions of the solar and bioenergy/biomass communities as we attempt to clarify them.

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