KDI-VOLTERA:

SUSTAINABLE ELECTRICITY FROM ABUNDANT THERMAL SOURCES

KD INNOVATIONS

KDI-VOLTERA GENERATES ELECTRICITY DIRECTLY FROM ABUNDANT HEAT SOURCES, WITHOUT ANY MOVING PARTS OR HEAT ENGINES.

BACKGROUND

Generation of Electricity from Heat Sources.

Most of the world's electricity is currently generated from heat, which is supplied by either combustion of fossil fuels (oil, coal and natural gas), thermonuclear reactions, or to a much lesser extent, from geothermal resources or concentrated solar radiation. Such generation of electricity from heat involves conversion of heat into mechanical work by a heat engine such as:

- A gas turbine
- Steam turbine
- Organic-cycle turbine
- Reciprocal piston engine

Once mechanical work is generated by heat engines at thermal power plants or smaller installations, it is then converted into electric energy by electromagnetic generators.

KDI-Voltera generates electricity **directly** from the heat source, without any moving parts or heat engines.

HIGH-GRADE VS. LOW-GRADE HEAT SOURCES:

A Clash of Environmental Hazard vs. Economic Efficiency.

Burning of fossil fuels produces heat with high temperature (so called high-grade heat) but is costly and environmentally hazardous. Greenhouse gasses implicated in manmade climate change, such as carbon dioxide, are released, as well as other pollutants (nitrous oxides, sulfur oxides, particulates). Oil and natural gas are expensive fuels that are scarce in many parts of the world. Coal is less expensive, but more damaging to the environment.

Thermonuclear reactions do not produce atmospheric emissions, however, they carry outsized risks of nuclear accidents, with extreme disastrous consequences. To safeguard against such risks, thermonuclear plants incorporate numerous safety features, which makes their construction highly expensive.

There are abundant sources of heat with relatively low temperature — or low-grade heat (LGH). For example, many industrial processes produce LGH as waste heat that is currently underutilized. The earth core is an overabundant source of geothermal energy, in the form of LGH. Solar radiation can be absorbed with simple and inexpensive absorbing collectors to produce LGH. While heat from such LGH sources has a very low-cost, approaching zero, they are currently underutilized for electricity generation. The reason for underutilization is that due to LGHs low temperatures, the system's Carnot efficiency is very low, leading to very large heat rates (amount of heat needed to produce a kwh of electricity; the inverse of efficiency), and correspondingly very high capital outlays.

Existing installations for electricity generation from LGH operate variations of the Rankine cycle and require large heat-flow investment – equipment needed to heat-up and evaporate the working fluid, plus reject heat machinery such as condensers, evaporative towers, etc. The expander turbines for Rankine cycles operating on LGH are also larger and costlier per kW than those operating with higher grade heat, due to the lower enthalpy per kg of working fluid that is being expanded by the turbine. Accordingly, the larger turbines take longer to heat-up to operating temperature, leading to these installations having inflexible operation regimes.

KDI-VOLTERA BASICS

KDI-Voltera is a patent-pending technology for direct conversion of LGH into electricity. At its core, the technology employs two electrode stacks operating at two different temperatures (hot and cold) and two liquid electrolytes circulating between the cold and hot electrode stacks. The electrolytes have different electrochemical temperature coefficients, and as a result, a voltage differential is created between the electrode stacks, that can be used to drive an electrical load. As the electrolytes circulate between the electrode stacks they undergo a forward and reverse electrochemical reactions of oxidation and reduction, while cycling between the two different temperatures. Thus the system operates with concurrent and interlocked electrochemical and thermodynamic cycles (FIGURE 1).

As a thermodynamic system, KDI-Voltera operates in a highly efficient fashion: both the electric energy harvesting in the HOT electrode stack, and the electrochemical regeneration of electrolytes in the COLD electrode stack are accompanied by *isothermal* heat absorption and heat rejection processes, respectively. In that regard, KDI-Voltera matches the theoretical Carnot thermodynamic cycle.

In addition, scientists at KD Innovations have achieved major breakthroughs in four main areas, which together make KDI-Voltera an extremely compelling technology for electricity generation:

1 **Technological concept based on fully liquid flow operation.** Using liquid aqueous electrolytes as a direct link between heat input and electric energy output has a distinct advantage of facile heat transfer. Liquids in general are the most efficient substances for heat transfer. Thus, heat can be easily added or rejected from a liquid electrolyte via well-established mechanisms and apparatuses such as plate heat exchangers and others.

As noted, the high heat rates of electrogeneration from LGHs makes the investment in the heat-handling infrastructure disproportionally larger. KD Innovations' exclusive use of liquid phase as the medium greatly facilitates the heat flow, as compared to other technologies. For example, Rankine cycle systems require transition through a vapor phase and costly investments in boilers and condensers.

2 **Innovative electrochemistry.** KDI-Voltera employs innovative electrochemistry based on inexpensive inorganic salts, which have shown temperature coefficients exceeding 2.5mV/°C. While some exotic metals and compounds may have higher electrochemical temperature coefficients, KD Innovations' chemistry is based on abundant salts, which affords sustainable scalability trajectory into hundreds of gigawatts in the future, without any supply constraints on materials.

3 **Inexpensive ion-selective membranes.** Many electrochemical systems — such as fuel cells or redox-flow batteries — require ion-selective membranes for the ionic currents that balance the flow of electrons in the outer circuit. Membranes with high ionic conductivities and good ionic selectivity, such as Nafion, can be costly and may constitute a substantial fraction of the total cost of the system.

Scientists at KD Innovations have developed a new membrane, specifically designed to work with the KDI-Voltera electrochemistry. The proprietary KD Innovations membrane is:

- Made of inexpensive materials and is highly cost effective
- Has excellent ionic conductivity and selectivity
- Is self-healing, meaning that defects and imperfections in the membrane that could potentially lead to leaks and intermixing of electrolytes are repaired instantaneously during the membrane operation

4 **Novel heat exchange technology.** As noted above, the all-liquid configuration of the KDI-Voltera system allows facile heat flow management from the hot reservoir to the electrolytes and the cold reservoir. In addition, heat recuperation from the exit of the hot electrodes, which is required for high-efficiency operation, necessitates heat exchange between the "spent" electrolyte from the hot electrode and the "regenerated" electrolyte from the cold electrode.

To meet these demands KD Innovations has developed a novel heat exchange technology, specifically suited to the needs of the KDI-Voltera system, which reduces cost and improves the efficiency and volumetric density of the heat transfer subsytems.

KDI-VOLTERA ELECTRIC GENERATION: KEY ADVANTAGES

1. **Low-cost to zero-cost primary fuel inputs.** KDI-Voltera utilizes low-cost or zero-cost LGHs from variety of sources: industrial waste heats, geothermal heat, solar heat. The fuel cost component of electricity generated by KDI-Voltera is miniscule or zero.

2. **Zero carbon emissions.** KDI-Voltera is a zero-emission technology, ideally suited for the stringent environmental demands of the twenty-first century.

3. **Low capital costs.** Technologies that harvest dilute energy sources for electricity generation, including renewable energy systems, usually suffer from very high capital costs. KDI-Voltera uses abundant materials and inexpensive components that would allow high capacity factor generation to be installed for less than $2,000/kW.

4. **Flexible load-following generation.** A kWh of electricity has different value depending on when it is supplied. KDI-Voltera has a very short turn-on time and can be used flexibly to meet demand needs. This is the highest value generation capacity, as compared to baseload, or to the supply intermittency of renewable systems.

5. **Ability to combine electricity storage with electricity generation.** Electricity storage is becoming an area of intense consideration to smooth-out demand fluctuations. Simple addition of electrolyte tanks to the basic KDI-Voltera system allows it to function as a highly efficient redox-flow battery (RFB) for electricity storage, in addition to electricity generation[1].

6. **Modular scale-insensitive technology.** Conventional generation systems are very scale sensitive with sharply higher costs per kW installed for smaller installations. This makes many local sources of LGH uneconomic for electricity generation. In contrast, KDI-Voltera is based on small manufactured modules — electrode stacks and heat exchangers — making it scale-insensitive and economical for small-scale local generation.

HEAT SOURCES FOR KDI-VOLTERA

Industrial Waste Heat. The industrial sector is the largest user of energy in the developed world. In the U.S. alone, the industrial sector consumes 28-30 Quadrillion BTUs (quads) annually, or about 30% of all domestic energy consumption. Roughly **one-third** of the energy consumed is discharged directly as thermal losses, and a significant fraction of those are suitable for KDI-Voltera electrogeneration. Additional sources of LGH, such as exhausts from gas pipeline compressors or landfill gas generators are not traditionally described as “industrial,” but are tangentially related.

Geothermal Heat. The heat content of the earth crust is immense, but currently geothermal energy utilization is limited to geological areas, in which a water carrier transfers heat from deep hot zones to near the surface, thus providing higher grades heat (well over 100°C). The KDI-Voltera has the ability to economically utilize lower grade heat, thus vastly expanding the economically-recoverable geothermal resource in numerous locations. One particularly interesting market for geothermal utilization of KDI-Voltera is **Japan**: a nation with limited conventional energy resources, located in a geologically active area with significant geothermal potential.

[1] RFBs are economically challenging systems, because of irreconcilable demands for low system costs and high round-trip efficiencies. To achieve low system costs, RFB require high power densities in the form of high voltages and high current densities, which cause side reactions/outgassing, and polarization losses, respectively, and therefore, reduced efficiency. KDI-Voltera, when operating as a RFB, resolves this issue by operating at low power densities and high efficiency. The higher system costs are paid for by the generation capacity of the system.

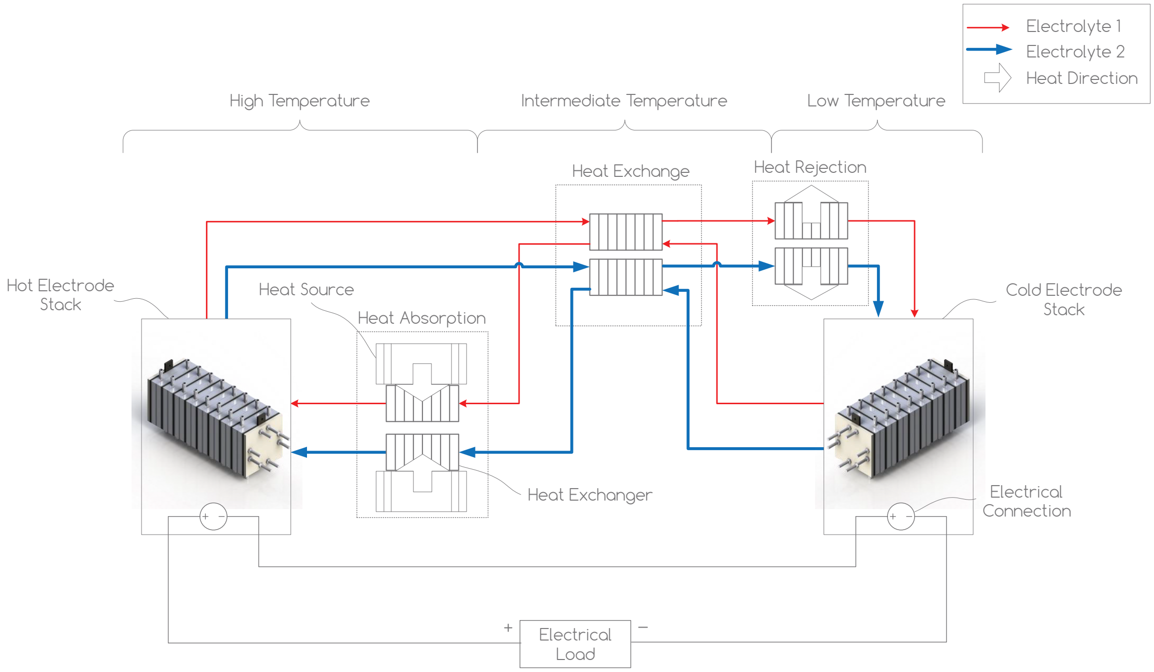

FIGURE 1. Schematic of a KDI-Voltera system

Passive Solar Heat. The sun's radiation is an immense source of abundant (but dilute) energy that could potentially supply all of the energy needs of humankind. Currently, the leading technologies for solar electricity generation are direct conversion with photovoltaic cells (PV) and concentrated thermal power (CSP). KDI-Voltera has the potential to economically utilize solar heat that is harvested with *passive* (non-concentrating) collectors. Such collectors produce low-grade solar heat and can be classified into two general scales:

- **Solar ponds** for large-scale solar harvesting and electricity generation. Solar ponds provide an extremely simple and cost effective way to generate LGH, requiring simply salt water and black lining of the pond.
- **Rooftop solar heaters** that are currently widely used for hot-water generation. KDI-Voltera would allow the same hot water to be used for distributed electricity generation.

The economic and technological considerations of using KDI-Voltera for solar generation via passive thermal collection versus PV and CSP are discussed further below.

KDI-VOLTERA INTEGRATES WITH THERMAL POWER PLANTS: Flexible Management of Power Generation and Coolant Use.

In addition to its implementation as standalone generation systems, KDI-Voltera can be integrated into conventional thermal power plants to provide flexible management of generation and coolant use. When storage tanks for electrolyte are added to the basic KDI-Voltera system, "fresh" electrolyte can be stored on site and deployed for additional generation during peak demand intervals (FIGURE 2).

For example, on a hot day, electricity demand can spike due to increased use of air-conditioning. The very same hot ambient conditions coincidentally put strain on the cooling systems of the power plant due to reduced availability of cooling, exactly when more coolant is needed for the spike in generation[2].

[2] This problem is especially acute in modern and enviromentally friendlier closed-cycle dry cooling systems, which rely on ambient air for cooling.

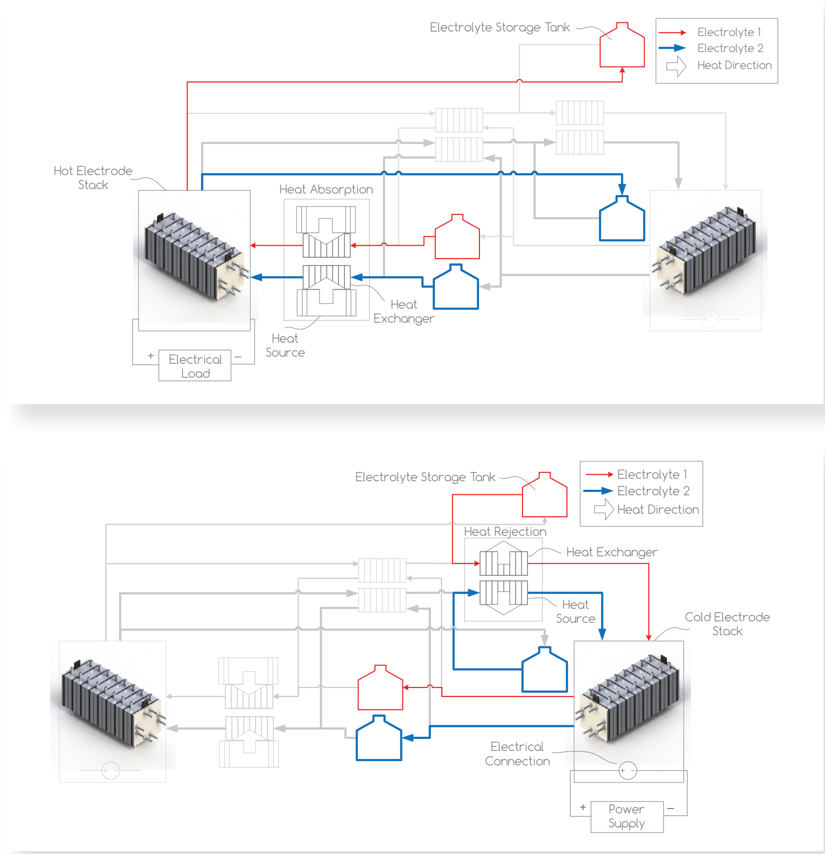

FIGURE 2. KDI-Voltera integration with a thermal power plant during "hot-ambient/high-demand" conditions (top) and "cool-ambient/low-demand" conditions (bottom).

With a supplementary KDI-Voltera on site, the operator may divert a stream of low-pressure steam from the bottom of a Rankine cycle turbine towards the hot electrode stacks, which are running on "fresh" electrolytes from storage tanks. This creates ***incremental*** generation capacity to meet the spike in demand. The high temperature electrochemical reaction proceeds with heat absorption, and the heat is absorbed in the products of the reaction, which are then stored in the tanks for "spent" electrolyte, while the cold side of the KDI-Voltera system is idle. Accordingly, there is no need for cooling since the electrolytes act as active heat absorbers.

During the night when electricity demand drops and temperatures are lower, the "spent" electrolyte is regenerated and heat is rejected in the cooler ambient environment. It should be noted that the electric energy and power generated during the day ***exceeds*** the one consumed during the night, i.e., roundtrip efficiency is higher than 100%. **This is due to KDI-Voltera being an electricity generation system and not simple energy storage, which usually operate at efficiencies of 75-80%.**

KDI-VOLTERA UTILIZATION OF SOLAR HEAT WITH PASSIVE COLLECTORS

Solar radiation is an overabundant and environmentally benign, but dilute source of energy. Conversion of solar energy into electricity is a rapidly growing industry, using mainly two technological approaches: photovoltaics (PV) and concentrated solar thermal power (CSP).

The main advantage of PV is that it transforms solar energy directly into electricity, however, it requires large area installations of rather sophisticated semiconductor-based solar cells. In addition, PV systems provide an entirely insolation-following supply without intrinsic capabilities for electricity storage or smoothing out.

In contrast, CSP uses large area mirrors as collectors, which convert solar radiation into high-grade heat that can be further converted into electricity using conventional turbines. The heat intermediation between solar collection and electricity generation adds an additional technological step, but affords two advantages: use of simpler devices for collection (simple mirrors vs. semiconductor cells) and capabilities for energy storage and supply flexibility through storing latent heat in a molten salt reservoir.

Despite the advantages of CSP, this technology has substantially lagged behind PV in terms of installed capacity. It appears that the cost of collecting mirrors is still very high and any cost advantage over semiconductor silicon cells is not sufficient to offset the additional infrastructure costs in thermal power generation: turbines, generators, cooling systems, etc.

KDI-Voltera has the potential to economically utilize solar energy by using passive (non-concentrating) collectors to generate low grade heat.

Such collectors can be classified into two general scales:

- **Solar ponds** for large-scale solar harvesting and electricity generation. Solar ponds provide an extremely simple and cost effective way to generate LGH, requiring simply salt water and black lining of the pond. The salt water generates vertical gradients in the pond — both for temperature and density — with temperatures at the bottom reaching 80-90°C, which is non-economical for conventional electrogeneration, but ideally suited for the KDI-Voltera technology. At the same time, the solar pond can effectively store heat overnight, so additional infrastructure for heat storage is not required.
- **Rooftop solar heaters** that are currently widely used for hot-water generation. KDI-Voltera would allow the same hot water to be used for distributed electricity generation. A small-scale KDI-Voltera system can allow a household to use the solar hot water for electricity generation as well, using the inexpensive rooftop collector for dual purpose.

	HEAT COLLECTION	ELECTRO-GENERATION	HEAT REJECTION	FUEL	SUPPLY LEVELING	DEMAND FOLLOWING	CO_2 COMPLIANCE
KDI-VOLTERA-SOLAR POND	$	$$	$$	0	0	0	0
PV	0	$$$	0	0	$$$	$$$	0
CSP	$$$	$$	$$$	0	$	$$$	0
NGCC	$	$	$$	$$	0	$$	$$

TABLE 1. Relative cost components of generation technologies

Table 1 illustrates the relative cost contributions of various factors towards the total costs of using four different technologies. KDI-Voltera with a solar pond collector has a very low cost of heat collection from the sun, and moderate costs of electrogeneration and heat rejection — using KD Innovations' proprietary electrochemical systems and heat exchangers respectively. Fuel costs, carbon compliance costs, and supply leveling costs, and demand following costs are zero.

PV systems do not require heat collection and heat rejection installations, but their electrogeneration component in the form of silicon solar cells has high costs. While the costs of manufactured cells have dropped to below $1,000/kW, it should be remembered that this is based on peak insolation, and the PV systems have small capacity factors. Therefore, a kW of installed PV capacity would produce much less electricity than 1 kW of a baseload installation. In addition, while the costs of manufactured PV cells have dropped, the costs of installing them in large area PV farms have kept up.

PV systems provide intermittent energy supply, based on the solar insolation variability. Leveling of the supply, and providing it on demand, requires investments in energy storage installations, which are still very costly.

A CSP solar thermal plant requires collection infrastructure, consisting of large scale mirrors, which are orders of magnitude more expensive than passive collection with solar ponds. The heat produced is of higher quality, and can surpass 250°C. The capital for the electrogeneration machinery via a conventional Rankine cycle is costlier than fossil fuel plants, which operate at significantly higher temperatures. Supply leveling requires investment in heat storage, while demand following is highly uneconomical since the turbines have long turn-on and heating-up times.

As a comparison to the aforementioned three solar technologies, a modern natural gas combined-cycle (NGCC) power plant has high efficiency and modest capital costs; the heat collection equipment consists of the boiler for the Rankine cycle, and the heat rejection is a standard cooling tower. However, NGCC consume natural gas fossil fuel, which in some parts of the world can be very expensive. While current NG prices in the U.S. are historically low, there have been severe price fluctuations in the past and, likely, in the future. With respect to demand fluctuations, NGCC operate mostly in baseload mode and any ramping up or down is costly. In addition, NGCC plants produce carbon dioxide (albeit at smaller quantities than coal-fired plants), which in a carbon emission regulation regime would incur costs in the form of carbon taxes or carbon credits.

SUMMARY

With an abundance of underutilized low-grade heat sources available, it's time for industry to direct its focus on **KDI-Voltera** as an innovative, low-cost and sustainable method of electricity generation.

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