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A FIELD GUIDE TO RENEWABLE ENERGY TECHNOLOGIES

SECOND EDITION

LAND ART **GENERATOR**

RENEWABLE ENERGY CAN BE BEAUTIFUL

Robert Ferry &
Elizabeth Monoian

ABOUT THIS GUIDE

The Land Art Generator works with communities around the world to design public art installations that cleanly provide renewable energy, water, and other human support systems at a variety of scales. These exceptional solutions for net-zero cities and communities designed as beautiful places for people and expressions of local culture are painting an attractive and positive vision of life in a post-carbon world.

We have put together this guide to renewable energy technologies as a useful resource for all designers, homeowners, urban planners, students, developers, artists, architects, landscape architects, engineers, and anyone else interested in a clean energy future. We hope that you will use this guide with every project you work on.

There is more out there than what we see in the everyday. In fact, you will see in this guide that there are dozens of proven methods of harnessing the power of nature in sustainable ways. Some interesting examples that may be applicable as a medium for public art installations include the organic thin-films that are flexible and offer interesting hues and textures, piezoelectric generators that capture vibration energy, concentrated photovoltaics that allow for interesting play with light, and custom solar laminations that can be printed on. The possibilities are endless, and new designs that can be artistically integrated into residential and commercial projects are coming onto the market all the time.

It is our hope that this guide will get you thinking creatively about ways to use technologies in innovative contexts, and that a clear understanding of the wealth of possibilities that are out there will help designers to conceive of the most creative net zero energy constructions.

The future we would like to see is one in which we are surrounded by the most diverse ecosystem of renewable energy technologies and landscapes, each a reflection of local culture and context.

The technologies catalogued in this guide have the power to save the world from the most catastrophic impacts of climate change. If implemented with creativity and artfulness, the infrastructures that will provide low-carbon climate solutions will also tell the story of the moment when we changed course in the nick of time, brought ourselves back in harmony with our one irreplaceable planet, and created an environmentally sustainable and socially just world where 10 billion people thrive in self-actualization.

In this future, where you will be surrounded by beautiful renewable energy generators, you will surely need a guidebook in order to know if that thing that you find so beautiful is a semiconductor-based artificial photosynthetic cell, a piezoelectric generator, a triboelectric fabric, or a dye-sensitized solar cell.

What is the future that you would like to see? Use this book and design your own renewable energy landscapes!

Learn more about the beauty of renewable energy at www.landartgenerator.org.

INTRODUCTION TO THE SECOND EDITION

When we published the first edition of the *Field Guide to Renewable Energy Technologies* in 2012 we knew that it would eventually require an update. In the past five years, advances in energy science and products have moved very quickly. This has meant that some of the technologies highlighted in our first edition have been overtaken by new advances, some of the innovative clean tech start-up companies that we listed in 2012 have come and gone, and conversion efficiencies have improved for some of the technologies. There are even a few newcomers that deserve their own listings.

In the past five years the changes to our energy landscapes and the renewable energy marketplace have been remarkable. The plummeting production cost of solar modules has created a sea change (better than a sea rise!) with exponential growth in newly installed capacity each year. With new power purchase agreements for utility-scale solar at under 2¢ per kilowatt-hour and solar + storage for 24 hour dispatchable power at around 3¢ per kilowatt-hour, renewable energy is already more affordable than electricity from coal-fired and gas-fired power plants in many parts of the world.

These market trends—along with the fact that we have less than a decade to cut atmospheric CO_2 emissions in half or else face dire climate consequences and feedback loops that could reverberate for thousands of years—mean that we are about to embark on a massive infrastructure investment and the implementation of renewable energy that will radically transform our visual landscapes and the design of our cities. We have not seen anything like this since the construction of the interstate highway system in the middle of the 20th century.

Today we are still dealing with the social damages wrought by highway corridors and overpasses that severed neighborhoods and entrenched socioeconomic and racial divides. The way that freeway infrastructure in the United States was implemented provides us with a warning across the decades and reminds us why it is so important that we ensure the infrastructure of the great energy transition will be designed in a way that helps to provide social justice and spatial justice solutions, rather than perpetuate inequities.

It is our hope that the technologies in this guide can be used as a way to provide energy for human thriving in ways that beautify public spaces and elevate art and culture in our lives.

This second edition has some added features, like the icons that distinguish electrical output from heat output in the conversion efficiency section of the solar category (electrical power is often derived from the heat, but some heat is always lost in the process).

We've also featured a selection of concept design proposals from the Land Art Generator Initiative design competitions that will give you a sense of what is possible with the creative implementation of these technologies.

This revised edition has been produced in coordination with the LAGI 2020 Fly Ranch design challenge held in partnership with Burning Man Project.

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DESIGNERS
Trevor Lee, Suprafutures

TECHNOLOGIES
solar photovoltaic, compact acceleration wind turbine

ANNUAL CAPACITY
30 MWh

A submission to the 2010 Land Art Generator Initiative design competition for Dubai/Abu Dhabi—LAGI 2010. Re-imagined in this rendering for a site in Pittsburgh, Pennsylvania.

BIO

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STORAGE

THERMAL

DIRECT NON-CONCENTRATING

CONVERSION EFFICIENCY = power out / solar power in = 45%–75% depends on system type and operating temperature

DIRECT NON-CONCENTRATING

Solar thermal can describe any system in which solar radiation is used to directly heat a medium that can retain and use the heat such as water, air, or solid wall.

Water can be used directly as domestic hot water in a building and for radiant floor heating (instead of relying on natural gas or grid electricity that might be generated from fossil fuels to heat the water). These systems typically utilize either flat plate or evacuated tube collection systems.

Solar heated water can serve as an energy storage mechanism to create thermal heat lag within occupied space such as with a Trombe wall.

Other systems that can help heat occupied space rely on air rather than water. The air is circulated through a cavity that is exposed to direct sunlight on the exterior of a building.

A very simple example of thermal energy is a greenhouse where the entire building acts as the solar energy collection device.

Solar thermal collectors can be mounted on the roof or the wall of a building, or in another location that has exposure to the sun.

Solar thermal is often used in combination with other energy-saving techniques such as ground source heat (geosolar systems), and solar thermal cooling (absorption refrigeration). These are referred to as solar combisystems.

One large installation can be used for "district heating" of multiple buildings within an eco-district.

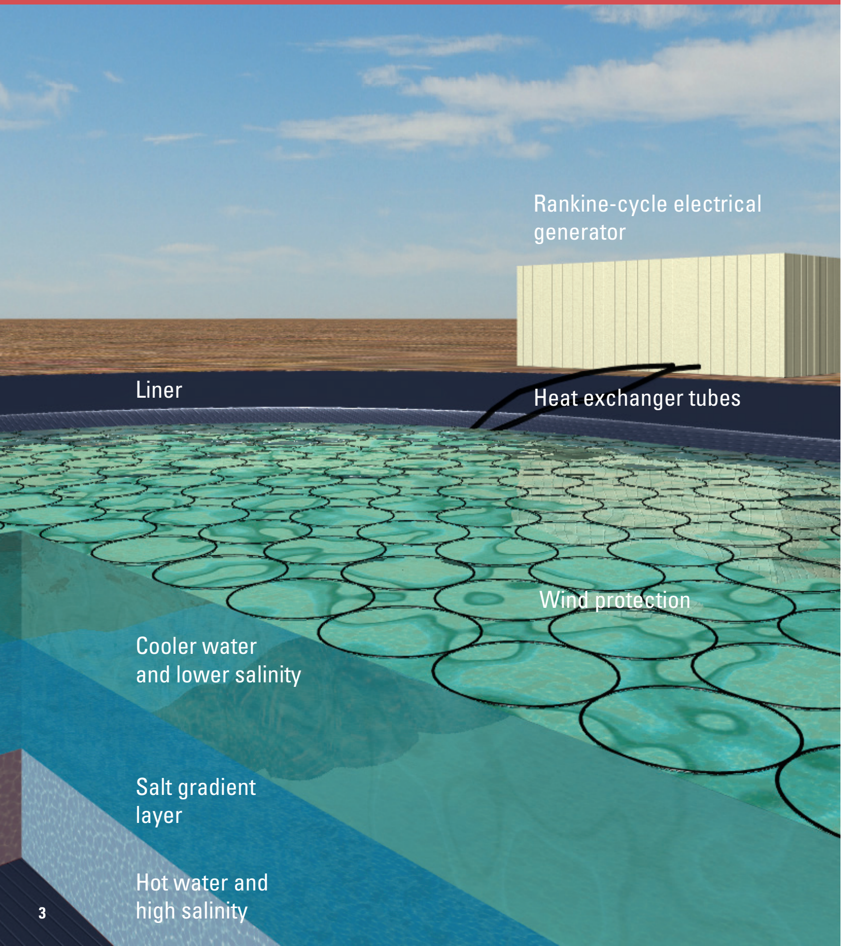
Evacuated tube system
Photo provided by Lumen Solar,
courtesy of Apricus Solar Hot Water.

THERMAL

SOLAR POND

CONVERSION EFFICIENCY = power out / solar power in = 20% (heat) or 5% (electricity)

*power input = insolation at the pond surface



SOLAR POND

A defining characteristic of a highly saline body of water is that it naturally stratifies into three layers of salinity. At the surface is a layer of low salinity and at the bottom is a layer of very high salinity. In between there is an intermediate insulating layer that keeps a heat exchange convention cycle from forming.

When exposed to solar radiation, heat is trapped in the bottom of the saltwater pond where temperatures can reach nearly 100 °C when water at the surface is only 30 °C.

The heat that is trapped at the bottom can be harnessed to power an organic Rankine cycle turbine or a Stirling engine, both of which convert heat into electricity without steam (they do not require temperatures in excess of the boiling point of water).

Via the Organic Rankine Cycle (ORC), water from the bottom of the pond is piped to an evaporator coil that heats a low-boiling-point fluid to pressurized vapor, driving a turbine. The vapor then passes to a condenser, where water from the top layer of the pond is used to cool the fluid back into liquid form after which it is then pumped back to the evaporator (with energy from a PV panel on-site).

Because saltwater is an excellent thermal heat sink, the solar pond produces electricity 24 hours per day regardless of weather conditions. Efficiency is greater in climates that receive higher average solar irradiance.

The Organic Rankine Cycle can be used to generate electricity from any low-heat water source such as geothermal sources between 70–120 °C that can be cooled by a separate water source from 0–30 °C.

SOLAR

THERMAL
CONCENTRATED
SOLAR POWER (CSP)

PARABOLIC TROUGH

CONVERSION EFFICIENCY = power out / solar power in = 25%

PARABOLIC TROUGH

The parabolic trough CSP design consists of a series of long, highly polished parabolic reflecting surfaces that focus sunlight onto an absorber tube running along the focal point of the parabola.

A heat transfer fluid (typically an oil) runs through the tube and is heated to approximately 400 °C to provide the thermal energy required to run a steam turbine.

The parabolic shape of the reflector allows the troughs to be oriented on a north-south axis and track the sun in only one rotational axis from east to west each day.

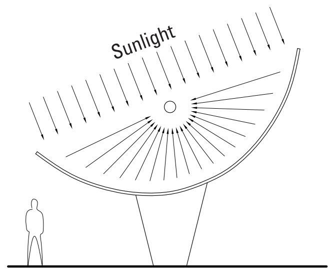
Reflectors can be made from curved tempered glass mirrors or from highly polished metal alloys. The curved mirror glass is more expensive to produce, but provides a more consistent and durable reflector with the highest reflectivity.

The engineering concept of CSP dates back to the 19th century inventions of Auguste Mouchout, Frank Shuman, and others. The discovery of vast petroleum reserves delayed the commercialization of the technology until the 1980s. Today global CSP capacity is growing rapidly, rising from less than 500 MW in 2008 to more than 5,000 MW a decade later.

Utility-scale CSP typically requires large tracts of land, but "Micro CSP" systems can be designed for installation on building rooftops.

We have proved the commercial profit of sun power in the tropics and have more particularly proved that after our stores of oil and coal are exhausted the human race can receive unlimited power from the rays of the sun.
—Frank Shuman,
The New York Times, July 2, 1916.

SEGS power plant at Kramer Junction in the Mojave Desert
Owned and operated by FPL Energy.
Image via Desertec-UK.



TRANSPIRE

DESIGNERS
Christopher Choa, Rachael Pengilley, Shaffee Jones-Wilson, Maged Hanna, Daniel Elsea, Hardik Pandit, Margot Orr, Michael Bonnington, Jules Cocke, Nick Taylor, Amelia Roberts

TECHNOLOGIES
concentrated solar power (parabolic trough)

ANNUAL CAPACITY
30,000 MWh

A submission to the 2010 Land Art Generator Initiative design competition for Dubai/Abu Dhabi—LAGI 2010.

THERMAL CONCENTRATED (CSP)

LINEAR FRESNEL REFLECTOR (LFR OR CLFR)

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{solar power in}}$ = 20%

LINEAR FRESNEL REFLECTOR

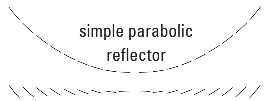
Linear Fresnel reflectors (LFR) use long, thin segments of flat mirrors to focus sunlight onto a fixed absorber located at a common focal point of the reflectors. Absorbers in LFR often contain multiple heat transfer tubes.

Similar to the more common parabolic trough, this single-axis tracking concentrated reflector system heats up a transfer fluid which in turn heats water to run a steam turbine (in the case of LFR, temperatures in the transfer fluid can reach 750 °C, although 300 °C is more common). One advantage of LFR is that the reflector mirrors are flat rather than parabolic in shape, which makes for a simpler mirror manufacturing process.

Systems can be set up to focus sunlight onto a single absorber (LFR) or onto multiple absorbers which is referred to as a compact linear Fresnel reflector (CLFR) system. CLFR design is obtained by alternating the angle of each reflector. This can lead to greater energy conversion efficiency of the overall system.

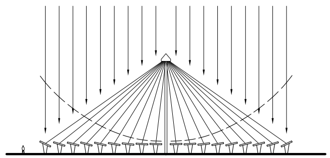
Kimberlina Power Plant in Bakersfield, California
Image courtesy of AREVA Solar.

Fresnel geometry allows flat surfaces to act in a way that mimics convex or concave mirror or lens optics.

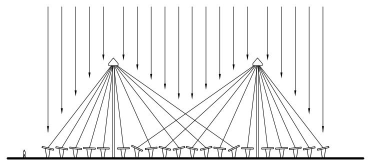


It was originally developed by French physicist Augustin-Jean Fresnel for use in lighthouses.

In a Fresnel reflector, a parabolic mirror is simulated in a segmented or "Fresnel" arrangement of flat mirrors.



LFR



CLFR

SUN RAY

DESIGNER
Antonio Maccà

TECHNOLOGIES
linear Fresnel reflector

ANNUAL CAPACITY
1,100 MWh

A submission to the 2018 Land Art Generator Initiative design competition for Mebourne—LAGI 2018.

SOLAR

THERMAL CONCENTRATED (CSP)

DISH STIRLING

CONVERSION EFFICIENCY = power out / solar power in = 32%

DISH STIRLING

Dish type collectors look like satellite receivers in their shape. They are parabolic, but unlike a linear parabola that concentrates along an axis, these are dish parabolas that concentrate light onto a single point. They can be one large dish, or an array of smaller reflectors as in the photo to the left.

They must rotate on a dual-axis to track the sun's position in the sky. At the single focal point is typically situated a highly-efficient Stirling engine which converts heat into mechanical energy with high efficiency. The mechanical energy is converted to electricity with a permanent magnet generator.

This type of concentrated solar thermal electricity installation rivals the best efficiencies of concentrator photovoltaic systems per similar land area and relies on simple mechanical technologies as opposed to semiconductors and microelectronics.

The Stirling engine is a type of external combustion engine of the reciprocating piston variety. It is named after Robert Stirling, who in 1816 invented the closed-cycle air engine.

The engine works on the principle that gas expands as its temperature increases. Expansion and contraction cycles will move a piston back and forth within a closed chamber. A magnetic piston moving through an electromagnetic field becomes a linear alternator, thus producing an electric current.

Stirling energy systems
Sandia National Laboratories in Albuquerque, New Mexico.

SOLAR

THERMAL CONCENTRATED (CSP)

SOLAR POWER TOWER

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{solar power in}}$ = 25%

SOLAR POWER TOWER

In this type of concentrated solar thermal power, an array of mirrors (heliostats) at the ground level tracks the sun's location in the sky and focuses sunlight onto a single collector positioned atop a central tower pylon structure where heat is transferred to run a steam turbine.

By using a high heat capacity material such as molten salt in the collector, energy can be stored to produce dispatchable power 24 hours a day and long after the sun has set (up to 17 hours of continuous electrical generation without solar feed).

The overall efficiency of the system increases as receiver size and temperature increases. Therefore solar power towers are typically sited in large open spaces where thousands of heliostats can maintain operating temperatures between 500 °C–1,000 °C.

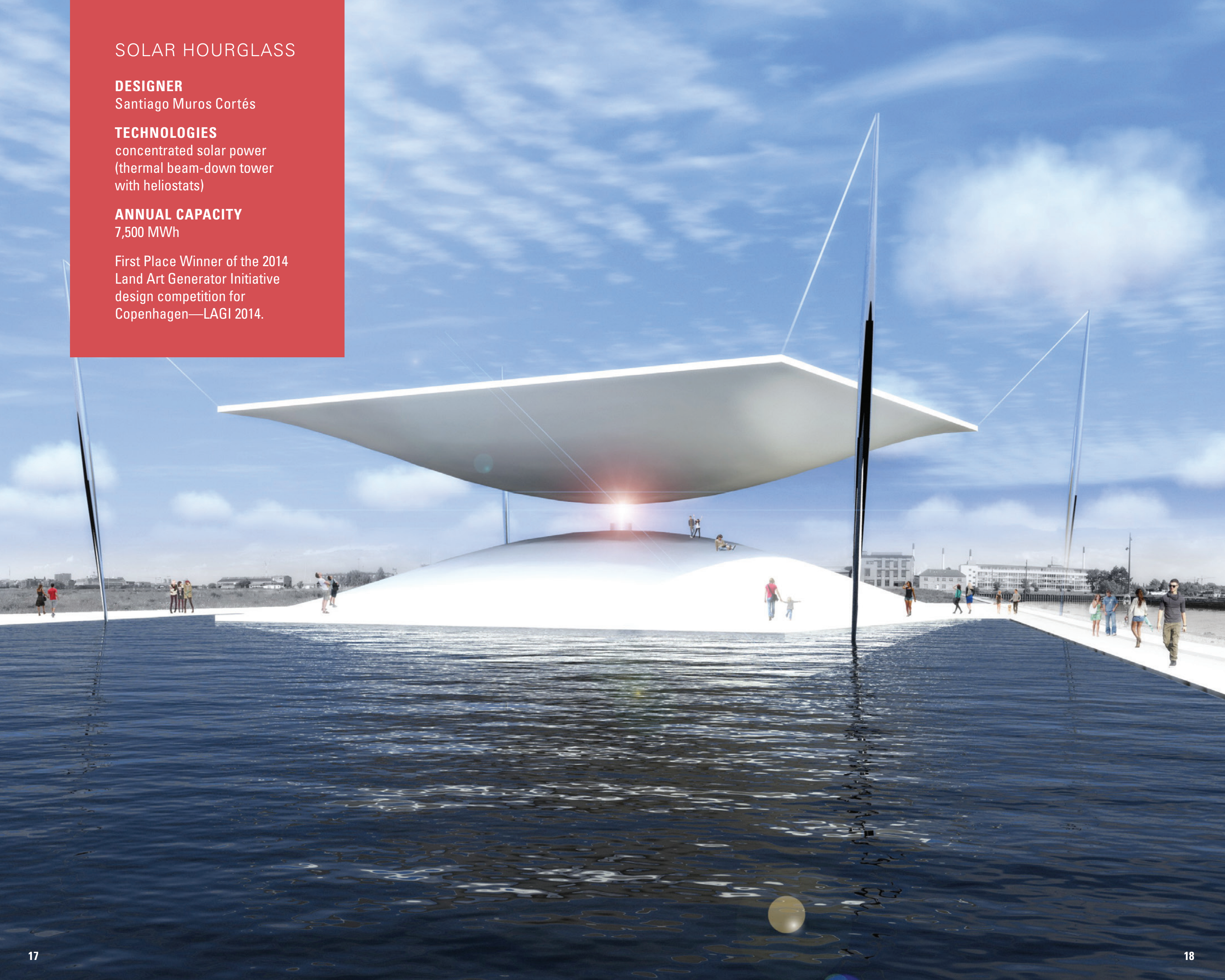
A variation—the beam-down tower—allows the entire heat transfer loop to be located at ground level, potentially increasing the overall efficiency of the system.

A "falling-particle" version of the receiver design drops sand-like ceramic particles through the beam of concentrated sunlight allowing for higher operating temperatures, which equates to more available energy and more efficient thermal energy storage.

Other design variations include a pit-power tower for a stadium mirror array and the Heliodyssee-Grand Four Solaire (solar furnace) in Odeillo France, which can reach 3,500 °C (more than twice the melting point of steel).

CSP could potentially even be integrated into buildings.

Gemasolar power plant in Spain
Owned by Torresol Energy (joint venture of SENER and Masdar). Image courtesy of Torresol Energy.



SOLAR HOURGLASS

DESIGNER
Santiago Muros Cortés

TECHNOLOGIES
concentrated solar power (thermal beam-down tower with heliostats)

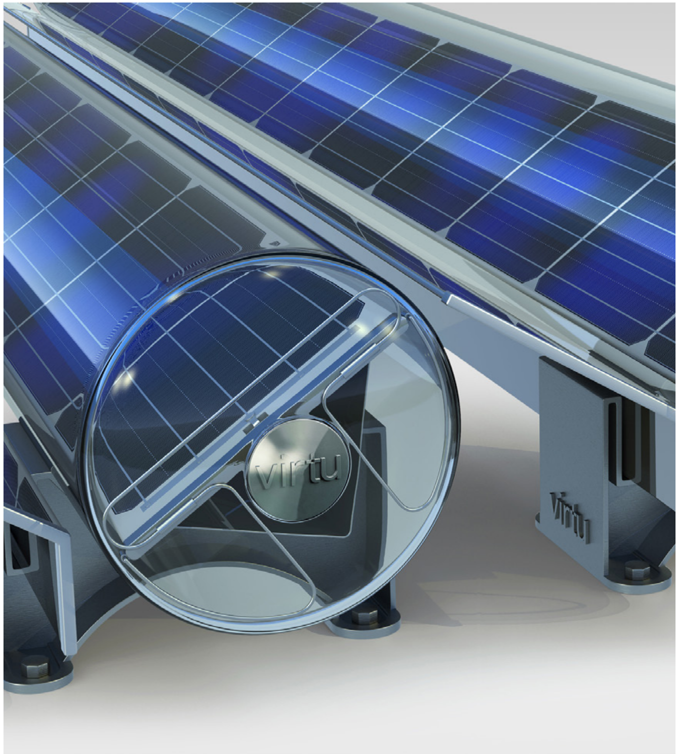
ANNUAL CAPACITY
7,500 MWh

First Place Winner of the 2014 Land Art Generator Initiative design competition for Copenhagen—LAGI 2014.

PHOTOVOLTAIC + THERMAL

INTEGRATED SYSTEM (PVT AND CPVT)

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{solar power in}}$ = UP TO 80% (20% + 60%)



PHOTOVOLTAIC THERMAL (PVT)

Known by a variety of names, such as photovoltaic thermal (PVT), concentrated photovoltaic thermal (CPVT) or combined heat and power solar (CHAPS), these integrated systems capture the waste heat energy generated from the inefficiency of the photovoltaic energy conversion process, and store it in a heat transfer fluid such as water for direct use.

PVT systems help to cool the operating temperature of the PV cell (which increases its conversion efficiency to electrical power) while providing hot water for domestic consumption at temperatures of approximately 80 °C. This water would otherwise require external energy (most likely derived from fossil fuels) to heat it.

Combined heat and power (CHP) systems use concentrated solar power, which can be achieved by various methods described in the pages above such as parabolic trough, parabolic dish, or linear Fresnel reflector.

Heated water can be used directly in domestic systems or can be heated again to produce steam (lowering the input energy required of the parallel system).

One commercial application for building-integrated PVT comes from the UK company Naked Energy. They make virtuPVT modules, which were incorporated into *The Oasis*, an entry to LAGI 2019 Abu Dhabi (following spread). *The Oasis* uses the hot water to power an absorption chiller for atmospheric water generation. The absorption chiller uses heat energy for refrigeration. The resulting chilled water is piped through the superstructure where condensation naturally occurs below the dew point temperature of the humid air, causing it to rain inside the desert artwork.

Photo of virtuPVT modules courtesy of Naked Energy.

THE OASIS

DESIGNERS
Aziz Khalili, Puya Khalili, Iman Khalili

TECHNOLOGIES
combined solar photovoltaic and thermal modules (Naked Energy VirtuPVT® or similar), hot water absorption chiller

ANNUAL CAPACITY
7,200 MWh and 18 million liters of freshwater

A submission to the 2019 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2019.

SOLAR

PHOTOVOLTAIC
ALL TYPES

$$\text{CONVERSION EFFICIENCY} = \frac{\text{power out}}{\text{solar power in}} = 3\%\text{–}42.5\%$$

PHOTOVOLTAIC SOLAR CELL

After its discover by A. E. Becquerel in 1839, the photovoltaic (PV) effect was demonstrated in various laboratory applications throughout the 19th century, but it was not until 1954 that the first commercially viable application of the technology was demonstrated by Bell Laboratories.

One square meter surface area (at sea level and perpendicular to the sun on a clear day) will receive up to 1,000 watts of solar radiation energy (insolation = 1,000 W irradiance/m^2). Conversion efficiency is a measure of how many of those 1,000 watts can be converted to electricity.

A 20% efficient solar panel will have a 200 W(p) capacity per square meter. The (p) stands for peak (also nameplate or rated capacity), and the panel will not always reach this level of output during field operation. The ratio between the rated capacity and the actual measured output over a year is the "capacity factor." The capacity factor for solar PV will vary based on geographic location from a high of 20% to below 10% in some locations. Environmental factors such as heat build-up, humidity, surface dust, orientation, shading, and airborne particulates can contribute to a lower capacity factor.

Methods of increasing the energy generated by solar modules include bifacial panels that collect reflected light from ground or rooftop at the back of the module, passivated emitter rear cell (PERC) technology that within the structure of the module itself bounces unabsorbed light back to the solar cell for a second absorption, light-trapping plasmonic-enhanced cells, and heterojunction with intrinsic thin layer (HIT) cells that surround crystalline silicon with ultra-thin amorphous silicon layers.

Monocrystalline silicon photovoltaic array
Image courtesy of Siemens AG, Munich/Berlin.

NEST

DESIGNER
Robert Flottemesch

TECHNOLOGIES
monocrystalline bifacial PERC solar modules with module level DC optimization

ANNUAL CAPACITY
6,633 MWh

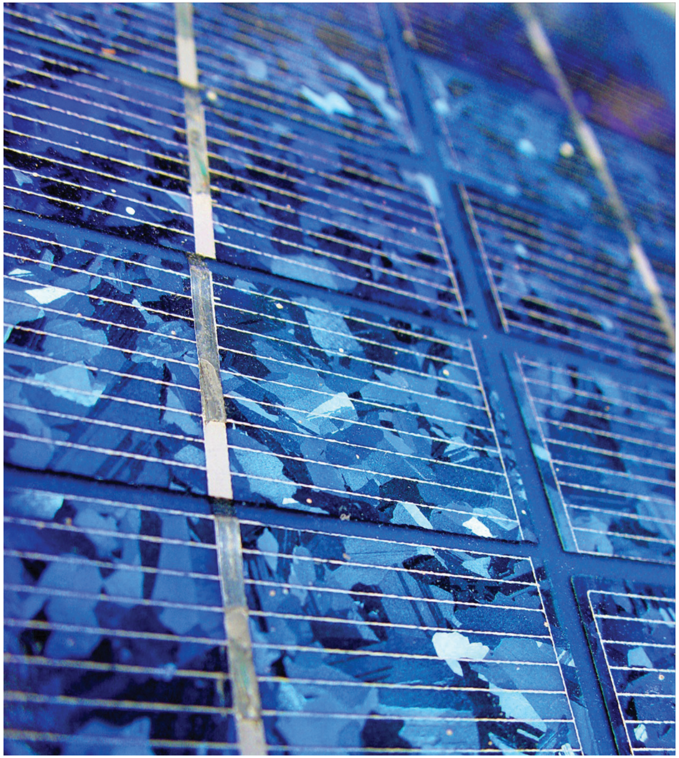
A submission to the 2019 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2019.

SOLAR

PHOTOVOLTAIC

CRYSTALLINE SILICON

CONVERSION EFFICIENCY = power out / solar power in = 18%–23%



CRYSTALLINE SILICON

Silicon (Si) is the fourteenth element of the periodic table and a semiconductor material that displays the photovoltaic effect. It is the most prevalent material employed in solar cells due to the abundance of silicon in nature. It can be used for solar wafers in either a crystalline (wafer) form, or in a non-crystalline (amorphous) form.

There are two types of crystalline silicon (c-Si): monocrystalline (mono-Si) and polycrystalline, also known as multicrystalline (multi-Si).

Monocrystalline is expensive to manufacture because it requires cutting slices from cylindrical ingots of silicon crystals that are grown with the Czochralski process, but it is the most efficient crystalline silicon technology in terms of energy conversion. Polycrystalline is easier to manufacture and can be cut into square shaped slices, but has slightly lower efficiency (approximately -5%). It is comprised of small crystals or crystallites.

Silicon is the most common metalloid found in nature making up 27.7% of the earth's crust by mass. It is typically found as silica (SiO_2) in sands rather than in its pure elemental form. Molten salt electrolysis can create pure silicon from silica with low energy input and without CO_2 emissions.

More commonly, high temperature furnaces (1,900 °C) create the condition in which silica is converted to pure silicon via reaction with carbon: $SiO_2 + 2\,C \rightarrow Si + 2\,CO$.

Polycrystalline can be tinted a variety of colors like the golden modules that make up the arabesque sphere of *Solar (ECO) System* on the following spread.

Polycrystalline silicon solar panel
Photo by Scott Robinson.

SOLAR (ECO) SYSTEM

DESIGNERS
Antonio Maccà, Flavio Masi

TECHNOLOGIES
photovoltaic panels

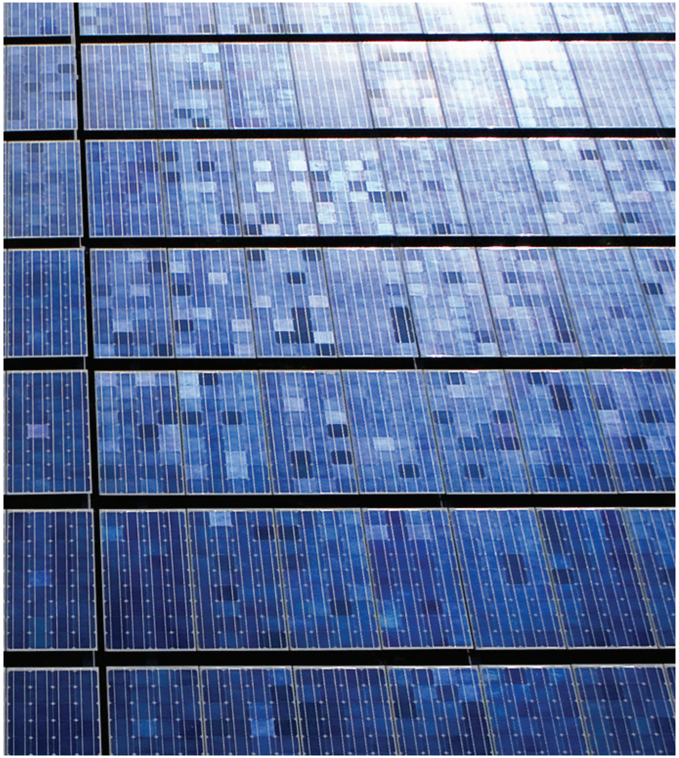
ANNUAL CAPACITY
1,000 MWh

A submission to the 2010 Land Art Generator Initiative design competition for Dubai/Abu Dhabi—LAGI 2010.

PHOTOVOLTAIC

THIN-FILM
AMORPHOUS SILICON

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{solar power in}}$ = 12%



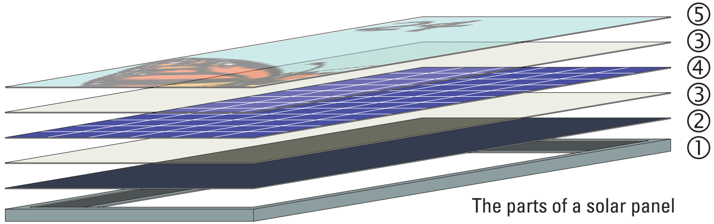
Photovoltaic installation at Real Goods Solar Living Center in Hopland, California
Photo by Cris Benton.

AMORPHOUS SILICON

Amorphous silicon (a-Si) is less expensive to produce than either mono or poly-crystalline silicon. It is non-crystalline, meaning that the atomic structure is more randomized. It operates at a lower efficiency than crystalline structures, but it can be fabricated so thin as to be flexible. Other types of thin-film silicon are protocrystalline and nanocrystalline (aka microcrystalline).

The efficiencies that are gained in the manufacturing process of thin-film photovoltaics can potentially offset the reduced conversion efficiency of the panels when figured over the life-cycle of the system, although by the late 2010s a-Si had lost its competitiveness in the market due to the rapidly declining cost of mono-Si.

A typical solar panel (or module) is composed of a frame ①, backsheet ②, adhesive layers ③, the solar cells ④, and the face glass ⑤.



The parts of a solar panel

The face glass can be clear or it can be tinted any solid color, be fritted with patterns, or be applied with a high transmittance printed film, like the artwork, *La Monarca*, on the following spread (film applied over mono-Si).

A solar panel can also be frameless (with the glass edges exposed), or bifacial, which means it has solar cells and face glass on both sides.

LA MONARCA, A LAND ART GENERATOR SOLAR MURAL ARTWORK

ARTIST
Cruz Ortiz

ART DIRECTION
Penelope Boyer

TECHNOLOGIES
monocrystalline Si photovoltaic with custom lamination

ANNUAL CAPACITY
2 MWh (four modules)

La Monarca is seen here visiting the San Antonio Zoo, reminding visitors about the importance of pollinators and the value of cross-border migrations of all kinds. Photo by Penelope Boyer.

SOLAR

PHOTOVOLTAIC

THIN-FILM NON-SILICON

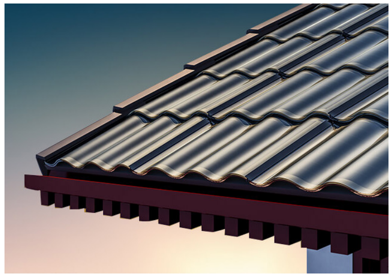
$$\text{CONVERSION EFFICIENCY} = \frac{\text{power out}}{\text{solar power in}} = 12\%\text{–}20\%$$

THIN-FILM NON-SILICON

As an alternative to silicon (Si), other semiconductor materials can be used for thin-film solar cells. They have been proven to have greater efficiency than thin-film amorphous silicon. To achieve their high performance they rely on multiple semiconductor materials. Each captures light energy most efficiently across a limited wavelength spectrum.

Copper indium gallium selenide (CIGS) has a conversion efficiency of about 20%. It can be manufactured to be very thin due to its high absorption coefficient, and can be printed onto thin foil substrates with nanoparticle inks and roll-to-roll manufacturing. Cadmium telluride (CdTe) has a conversion efficiency of about 16% and potentially offers cost advantages over CIGS. Copper zinc tin sulfide (CZTS) is the most environmentally-friendly thin-film (only uses abundant and non-toxic materials), and has an efficiency of nearly 12%.

The levelized cost of energy for non-silicon systems when compared to silicon-based PV depends greatly on the global market cost of silicon at the time of manufacture.



Example of printed CIGS flexible thin-film embedded in Japanese-style roofing tiles by Hanergy Mobile Energy Holding Group Co., Ltd.

Sempra Generation's CdTe Copper Mountain Solar facility
CdTe modules by First Solar. Image courtesy of Sempra U.S. Gas & Power, LLC.

SOLAR SEESAW

DESIGNERS
Luca Fraccalvieri,
Ahmad Nouraldeen

TECHNOLOGIES
flexible thin-film solar (CZTS) (Crystalsol™ or similar), kinetic energy harvesting pavers

ANNUAL CAPACITY
2,800 MWh

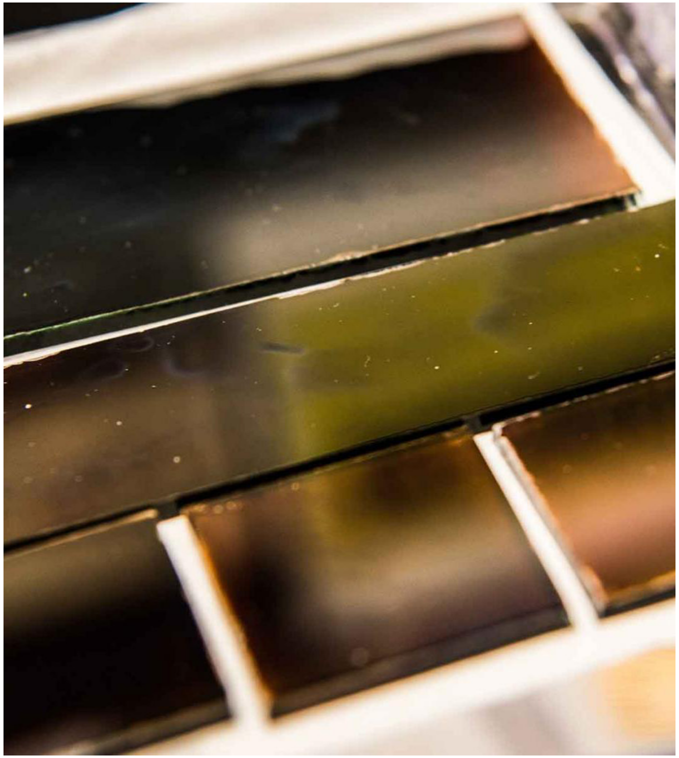
A submission to the 2019 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2019.

SOLAR

PHOTOVOLTAIC

PEROVSKITE

CONVERSION EFFICIENCY = power out / solar power in = 20%–28% (40% theoretical)



PEROVSKITE

A perovskite is any material with a crystal structure similar to that found in the mineral calcium titanium oxide, first discovered in the Ural mountains of Russia by Gustav Rose in 1839 and named after Russian mineralogist L. A. Perovski (1792–1856). Other natural minerals have the same crystal structure, including loparite and bridgmanite.

In 2009 Tsutomu Miyasaka and his team at the University of Tokyo discovered that synthetic materials with perovskite structures such as metal halide perovskites can function as semiconductors for solar cell construction, replacing silicon or other semiconductor materials. Since 2009, the measured conversion efficiency of perovskite solar cells has risen dramatically from 3.8% to rival the best silicon-based cells. By using perovskite material in tandem with silicon, a 28% conversion efficiency has been measured by Oxford Photovoltaics.

The high absorption coefficient of perovskites enables ultra-thin films of only 500 nanometers to absorb the complete spectrum of visible light, opening up endless possibilities for flexible and highly efficient solar modules.

Before perovskite solar cells become widely available commercially, they still need to overcome the problems of scaling and stability. Perovskite solar cells are susceptible to mechanical fragility and degradation from moisture, oxygen, temperature, and ultraviolet light.

Recent advancements (e.g. EPFL) have demonstrated the feasibility of larger-scale perovskite solar modules that can overcome stability problems over durations of one year.

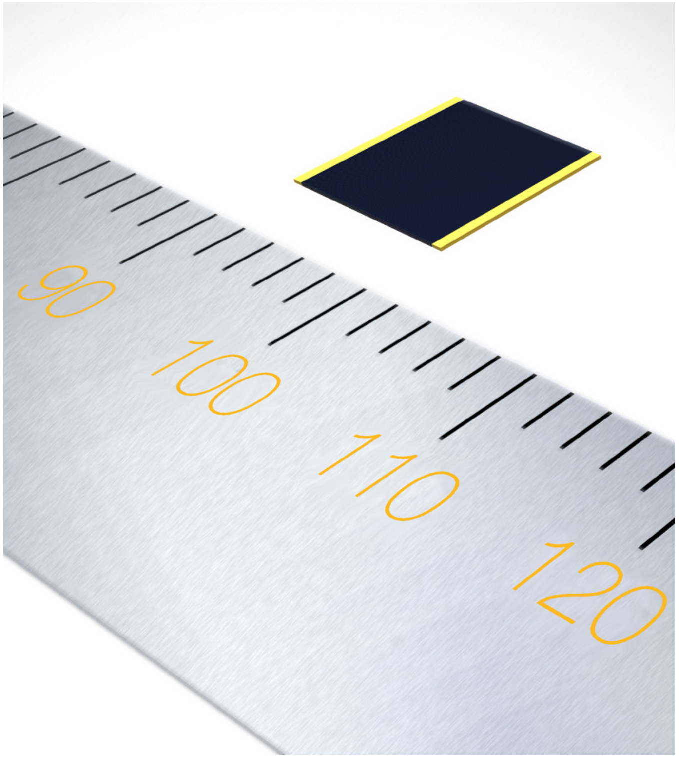
Perovskite ink applied to substrate.
Photo by Dennis Schroeder, courtesy of National Renewable Energy Laboratory.

SOLAR

PHOTOVOLTAIC

MULTI-JUNCTION

CONVERSION EFFICIENCY = power out / solar power in = 25%–45%



Multi-junction cell

MULTI-JUNCTION

Multi-junction cells are capable of achieving high conversion efficiencies because they are able to capture electrons within multiple wavelengths of light.

In contrast, more conventional single junction cells are limited to the energy within a partial spectrum (the remaining light either reflecting away or being lost to heat energy).

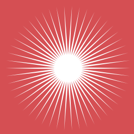
Multi-junction cells take advantage of multiple materials, each of which best capture a particular light wavelength (color spectrum) for solar-to-electricity conversion. This can lead to very high conversion efficiencies, even above 40%.

The technology was first developed for use in space explorations such as the Mars rover missions, and is still used for aerospace applications.

Because of the manufacturing expense of these "tandem cells," terrestrial commercial application has been generally limited to concentrator photovoltaic (CPV), which requires high PV performance within a small area of concentrated sunlight.

Various techniques use different substrate materials and can be either two-junction or three-junction. Some substrate materials that are used are: Gallium arsenide, germanium, and indium phosphide. Because the film is deposited (epitaxially) onto a monocrystalline substrate, the applied layers take on the lattice structure of the substrate crystal while maintaining thin-film properties.

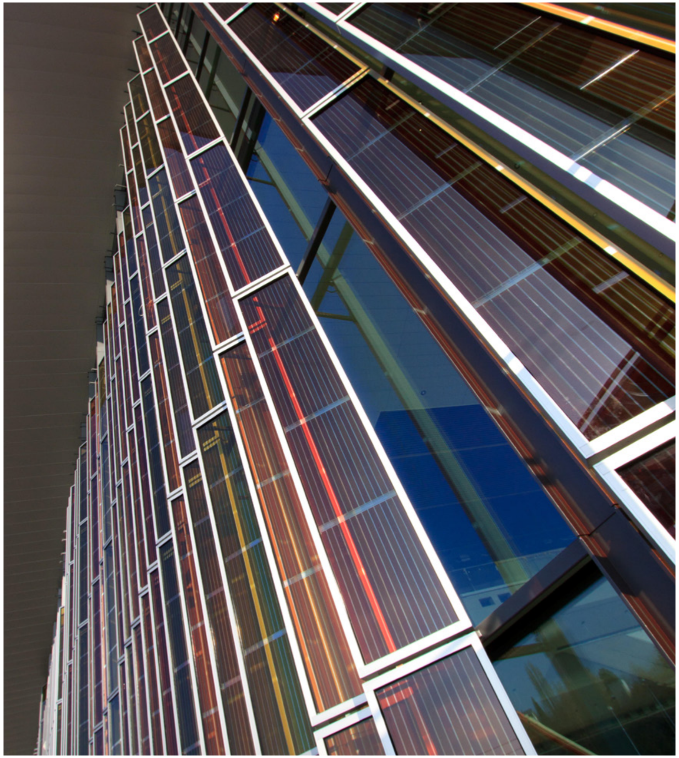
SOLAR



PHOTOVOLTAIC

THIN-FILM
DYE-SENSITIZED SOLAR CELL (DSSC)

CONVERSION EFFICIENCY = power out / solar power in = 9%–11%



DYE-SENSITIZED SOLAR CELL (DSSC)

Techniques for creating dye-sensitized solar cells (DSSC) are simple and the materials are very low cost, but the conversion efficiency is also below that of solid-state semiconductor technologies (DSSC is the most efficient of the "third generation" thin-films). This technique was invented in 1991 by Michael Grätzel and Brian O'Regan at EPFL. The DSSC solar cell is alternatively known as the Grätzel cell. They are a type of photoelectrochemical cell (PEC).

They have the characteristic of being semi-transparent, flexible, and are very durable. They also function comparatively better than other PV technologies in low light levels and indirect light. Because they are relatively inexpensive to produce they have one of the lowest price/performance ratios, and despite their lower conversion efficiency are therefore competitive with other types of PV technology in terms of levelized cost (price per kWh over the lifetime of the installation).

Because of the existence of liquid electrolyte within the DSSC cells, the temperature must be maintained within certain bounds.

The liquid also acts as a solvent over time. This, and the volatility of the dyes under UV light, mean that details of the material housing assembly are critical.

DSSC installation at Ecole Polytechnique Fédérale de Lausanne (EPFL). Design: Daniel Schlaepfer and Catherine Bolle. Architect: Richter Dahl Rocher & Assoc.
Photo © Solaronix SA, Switzerland

RENEWABLE OASIS

DESIGNER
Kyriakos Chatziparaskevas

TECHNOLOGIES
dye-sensitized solar cell (DSSC) laminated in ETFE sheets, piezoelectric energy harvesting from wind and pavement

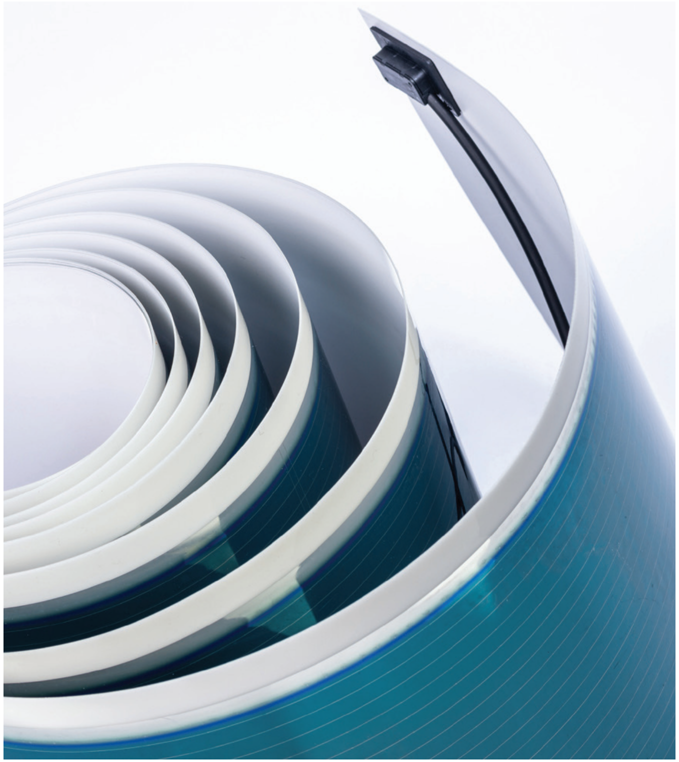
ANNUAL CAPACITY
500 MWh

A submission to the 2019 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2019.

PHOTOVOLTAIC

THIN-FILM
ORGANIC PHOTOVOLTAIC (OPV)
OR POLYMER SOLAR CELL

CONVERSION EFFICIENCY = power out / solar power in = 8%–16%



Organic photovoltaic sheet
Produced by Heliatek.

ORGANIC PHOTOVOLTAIC

OPV (also known as OSC for organic solar cell) uses organic polymers to absorb sunlight and transmit electrical charges. Organic PV can be manufactured in solutions that can be painted, printed, or rolled onto proper substrate materials. Current OPV technology has peak power output of about half that of mono-crystalline silicon PV per unit area, but its production cost, flexibility, and good performance in indirect light mean that it can—in some cases—outperform conventional PV over time.

Examples of small-scale uses for OPV can be seen sewn into fabric such as in backpacks, laptop cases, tents, and jackets. The energy generated by a backpack utilizing this technology, for example, is sufficient to charge portable electronic devices and to provide power to lights. Its versatility in design makes it perfect for building-integrated applications.

Hexagonal organic photovoltaic modules
Produced by OPVIUS and installed at the German Pavilion at the 2015 EXPO Milano. Photo by LAPP Group.

BEYOND THE WAVE

DESIGNERS
Jaesik Lim, Ahyoung Lee, Sunpil Choi, Dohyoung Kim, Hoeyoung Jung, Jaeyeol Kim, Hansaem Kim

TECHNOLOGIES
organic thin-film

ANNUAL CAPACITY
4,229 MWh

A submission to the 2014 Land Art Generator Initiative design competition for Copenhagen—LAGI 2014.

SOLAR

THERMOPHOTOVOLTAIC (TPV)

CONVERSION EFFICIENCY = power out / solar power in = Greater than 50% PV + TPV (theoretical)

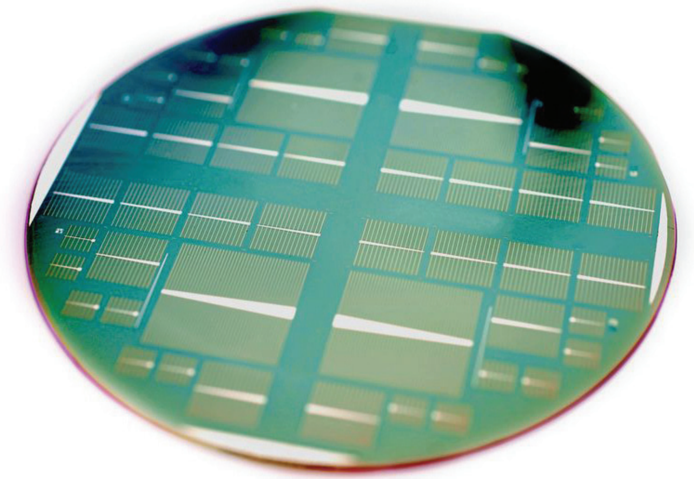


Image courtesy of IMEC.

THERMOPHOTOVOLTAIC (TPV)

TPV converts heat energy directly into electricity via photons.

A TPV system consists of a thermal emitter and a photovoltaic diode. For the most efficient operation the temperature of the thermal emitter should be about 1,000 °C above the temperature of the photovoltaic diode cell, but some energy could be created from smaller differences in temperature.

TPV employs photovoltaic technology but does not necessarily rely on the sun as the emitter of the photon energy.

Potential exists with TPV to see significant increases in the overall efficiency of solar power systems by converting residual heat energy that is otherwise wasted.

PHOTOVOLTAIC

CONCENTRATOR PV (CPV)
LOW (LCPV) = 2–100 SUNS
HIGH (HCPV) = 300–1,000 SUNS

CONVERSION EFFICIENCY = power out / solar power in = UP TO 42%

Concentrator PV
Image courtesy of SolFocus, Inc.

CONCENTRATOR PV (CPV)

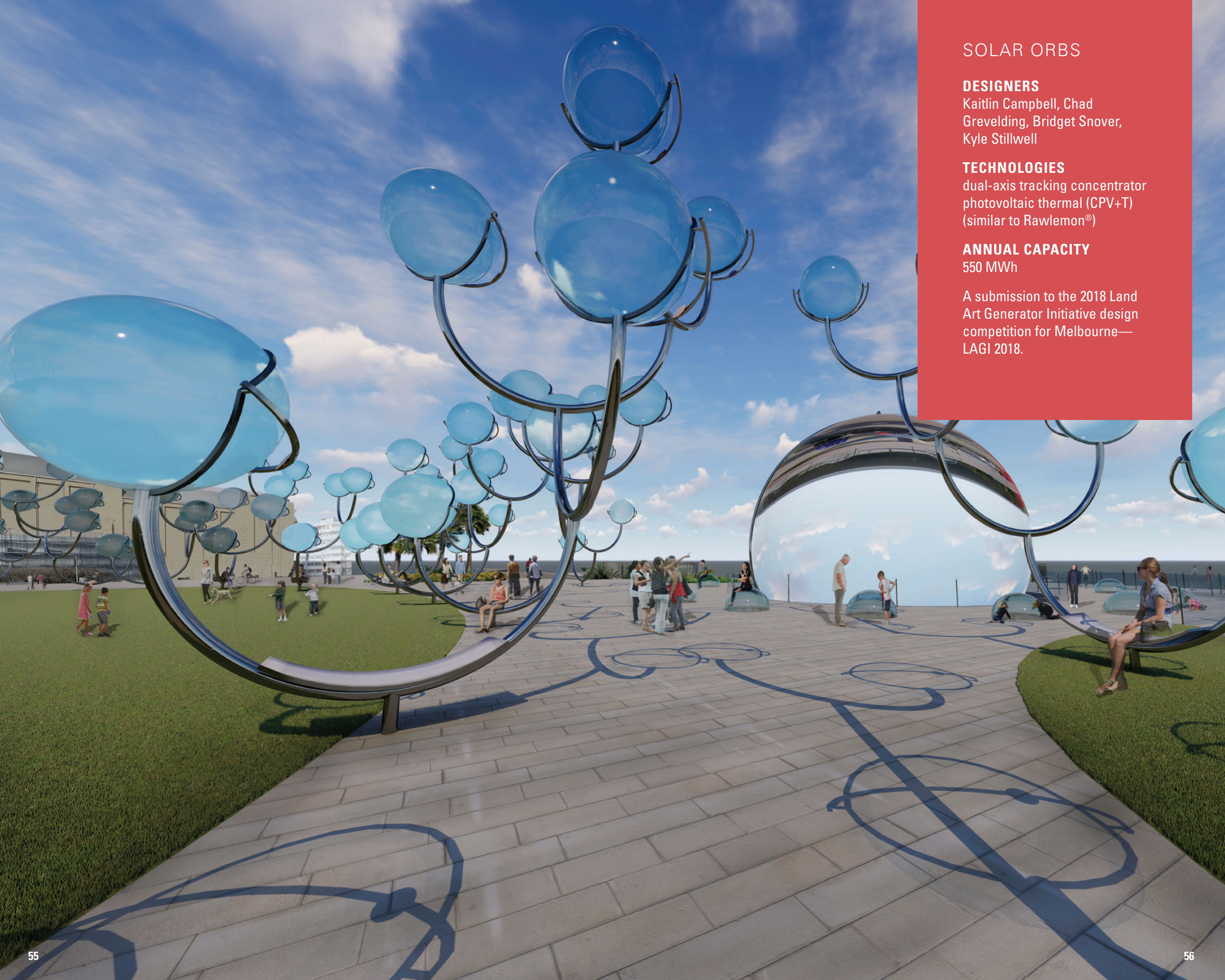
CPV employs photovoltaic cells, but rather than rely on the standard intensity of naturally occurring solar radiation energy, the CPV system concentrates the sunlight and directs a magnified beam onto a smaller area solar cell specifically designed to handle the greater energy and heat.

Because the solar cell can be much smaller, the amount of semiconductor material required is far less for the same watt capacity output when compared to non-concentrator PV systems. This can reduce the construction cost per watt capacity of the overall system. Savings are offset by the complexities of dual-axis tracking and parabolic mirror fabrication. Because of the increased heat on the solar cell, CPV installations often require the integration of heat sinks or other cooling apparatus.

The magnification of the sunlight can be low, medium, or high concentration, and is accomplished by a number of methods, the most common of which is a Fresnel lens. Other designs like the one shown here utilize parabolic reflectors. Some CPV systems employ parabolic troughs that direct sunlight onto a linear solar cell in which case they require only single-axis tracking.

A variation on CPV developed by Andre Broessel, the founder of Rawlemon®, uses a water-filled glass or plastic sphere as the concentrator lens. The multi-junction solar cell orbits the sphere opposite the sun throughout the day. The proposal to LAGI 2018 Melbourne, *Solar Orbs*, incorporates this idea into public art (following spread).

Another variation on CPV is the total spectrum collector which separates light with a prism into different spectrums best suited to different solar cell types.



SOLAR ORBS

DESIGNERS
Kaitlin Campbell, Chad Grevelding, Bridget Snover, Kyle Stillwell

TECHNOLOGIES
dual-axis tracking concentrator photovoltaic thermal (CPV+T) (similar to Rawlemon®)

ANNUAL CAPACITY
550 MWh

A submission to the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

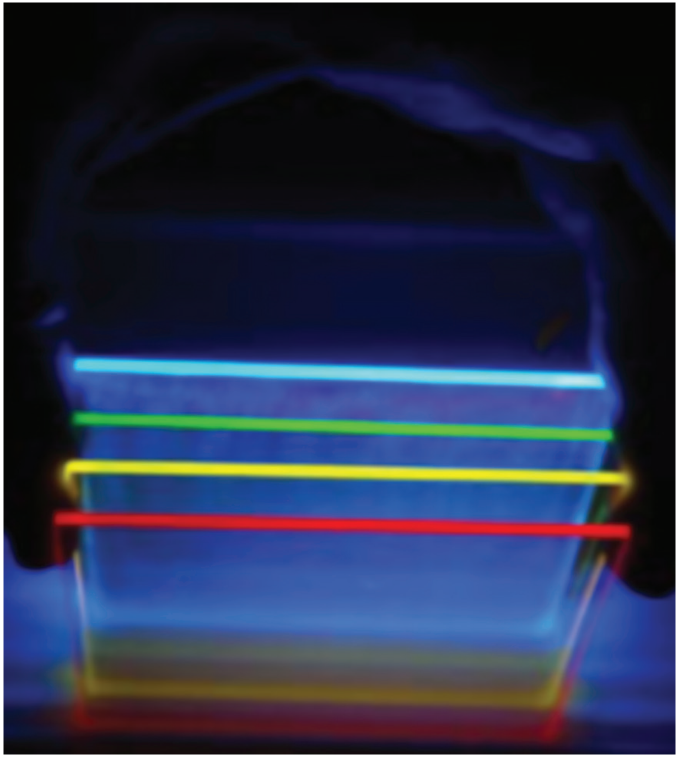
SOLAR

PHOTOVOLTAIC

LUMINESCENT SOLAR CONCENTRATOR (LSC)

$$\text{CONVERSION EFFICIENCY} = \frac{\text{power out}}{\text{solar power in}} = 7\%$$

STILL IN THE RESEARCH STAGE OF DEVELOPMENT



LUMINESCENT SOLAR CONCENTRATOR (LSC)

The application of special dyes to the surface of a pane of glass or plastic can cause a certain spectrum of light to be diverted at concentrated levels directly to the edges of the glass, where it can then be collected by a solar cell that is calibrated specifically for that wavelength. All other light wavelengths continue uninterrupted through the glass pane, which appears almost completely transparent.

The use of LSC for greenhouse applications has been considered since the 1970s (Weber & Lambe, 1976; Goetzberger & W., 1977).

The potential for building integration in windows of all kinds is enormous. If entire commercial buildings can be economically clad in LSC-panel curtain walls, the scale would overcome the low conversion efficiency and provide a significant percentage of the building's energy demand without any visual impacts to the design.

As of 2018, ClearVue® PV—based in Perth, Australia—is bringing this technology to market with functioning installations of up to 70% clear PV glass in buildings and bus shelters. 90% of UV and IR radiation is captured by the spectrally-selective film, which reduces the solar heat gain within the building, leading to lower air-conditioning load. ClearVue® also offers imaging on the glass in partnership with Zurreal. The result is akin to a stained glass artwork that also generates electricity with a rated output of 30 watts per square meter (3% conversion efficiency).

Research continues to improve efficiency of transmission and stability of dye treatment.

Example of luminescent solar concentrators
Image courtesy of MIT and researchers Marc Baldo, Michael Currie, Jon Mapel, and Shalom Goffri. Photo by Donna Coveney.

THE RAINBOW SERPENT

DESIGNERS
Arthur Stefenbergs, Lucian Racovitan, Keith Mc Geough, Ovidiu Munteanu

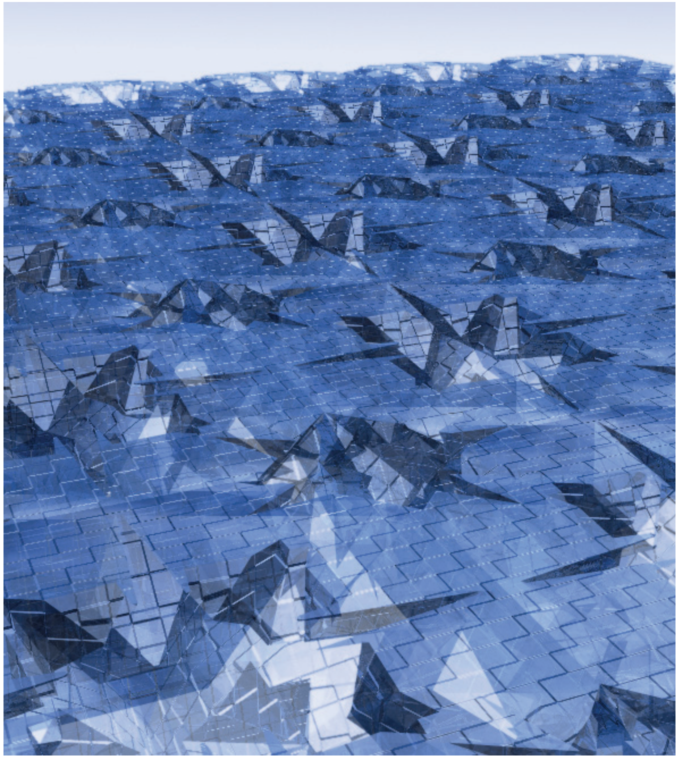
TECHNOLOGIES
luminescent solar concentrator (LSC), kinetic energy harvesting

ANNUAL CAPACITY
90 MWh

A submission to the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

SOLAR

EMERGING PHOTOVOLTAIC



EMERGING PHOTOVOLTAIC

3D Cells and Nanostructures

Whereas a standard panel solar cell will typically reflect 20%–30% of the light that strikes its surface, a 3D cell relies on a geometry that can recapture the reflected light onto adjacent surfaces, thus increasing the efficiency of the entire system over the same surface area of installation. Use of multi-junction technology and perovskite materials in combination with 3D solar cell geometry has the potential to see applications in CPV systems with an energy conversion efficiency of 50% or greater. Plasmonic solar cells (PSC) use nanoparticles on the surface of a solar cell to scatter and trap more light within the cell.

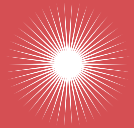
Infrared and Ultraviolet Solar

Experimental research is ongoing to develop methods of converting infrared and UV light into electrical power. Since infrared solar radiation energy is radiated back from the earth during the night, a system to capture it could potentially provide energy 24 hours a day. A team of researchers at Idaho National Laboratory, the University of Missouri, and the University of Colorado are working to develop nanoantennas (nantenna) that can collect both solar heat energy and industrial waste heat energy. The flexible film would be able to convert up to 90% of available light across multiple spectrums.

Quantum Dot Solar

The theoretical limit of solar cell conversion efficiency is as high as 86% if we could only find the perfect mix of materials. Synthesizing ideal semiconductor particles could potentially get closer to this kind of efficiency, although the technology remains experimental. In 2019 the University of Queensland recorded a conversion efficiency of 16.5% using quantum dots.

SOLAR



PHOTOELECTROCHEMICAL CELL (PEC)

CONVERSION EFFICIENCY = power out / solar power in = 10%

PHOTOELECTROCHEMICAL CELL (PEC)

PEC are solar cells that transform solar energy directly into electrical energy. Instead of using a solid-state semiconductor as the light absorbing material, PECs use an electrolyte material, which can be fluid (dye-sensitized solar cell) or solid (solid state PEC).

A circuit is created via a semiconducting anode and a metal cathode which are both in contact with the electrolyte.

Other types of PEC can be used to harness solar energy directly for purposes of electrolysis to create hydrogen—a stored fuel. In this system, water acts as the electrolyte solution. Hydrogen and oxygen form around the anode when exposed to sunlight. The resulting hydrogen can be stored and used to generate electricity in a hydrogen fuel cell where the only by-product is water.

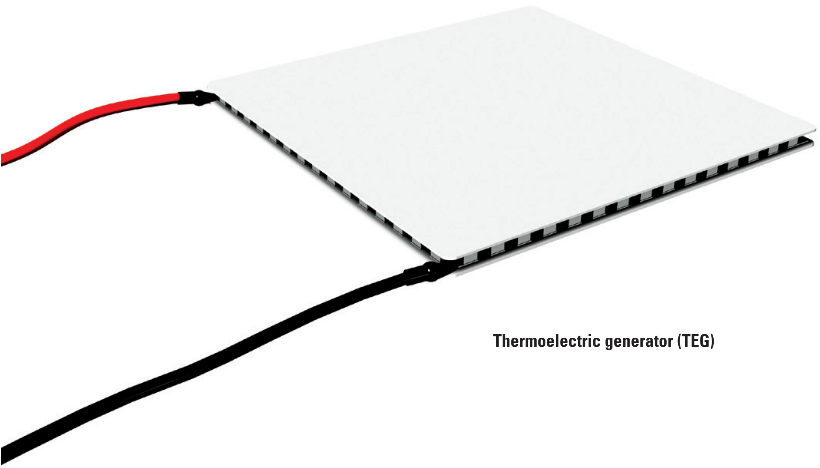
One of the technical obstacles to greater proliferation of PEC-type electrolysis for hydrogen generation is the corrosive effect of the electrolyte solution on the semiconductor anode.

Sometimes you may hear this technology referred to as "artificial photosynthesis."

Photoelectrochemical cell by Professor Michael Strano et al. Image courtesy of MIT. Photo by Patrick Gillooly.

THERMOELECTRIC

$$\text{CONVERSION EFFICIENCY} = \frac{\text{power out}}{\text{solar power in}} = 6\%\text{–}10\%$$



Thermoelectric generator (TEG)

THERMOELECTRIC

Thermoelectric systems convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" (or "thermoelectric effect"). This describes why an electric current is created between two different metals that are at different temperatures.

The voltage generated can be as high as 41 microvolts per degree kelvin difference using the right combination of metals.

Thermoelectric cooling takes advantage of the reverse effect, wherein an electric current is provided to a similar device, thus creating a difference in temperature between the two sides of the device. Known as the Peltier effect, this can be used to remove heat from an object or space.

Thermoelectric systems have the potential to increase the overall efficiency of photovoltaic panels by harnessing the heat energy that would otherwise be wasted, and at the same time increasing the operating efficiency of the PV panels.

Aaswath Raman, an assistant professor of materials science and engineering at the University of California, Los Angeles, has demonstrated the production of electricity from the thermal difference between radiative bodies (like buildings) at night and the cold of outer space by using a thermoelectric device. It generates 25 milliwatts of power per square meter of area.

SOLAR

SOLAR UPDRAFT TOWER

SOLAR CHIMNEY

CONVERSION EFFICIENCY = power out / solar power in = APPROX. 2%

SOLAR UPDRAFT TOWER

A solar updraft tower combines the stack effect with wind turbines located at the base of a very tall tower. The tower is surrounded by a large greenhouse at ground level where air is constantly being pulled in by convection and heated.

With a sufficiently tall chimney tower structure, the convection current moves air from the greenhouse area into the bottom of the tower and up to the open mouth at the top. As air passes into the base of the tower, it drives wind turbines located there.

The application of the updraft tower principle could even be applied to double-skinned super tall buildings.

The stack effect is the natural property of air within a closed space to rise vertically with buoyancy when heated in relation to ambient air temperature. The greater the heat differential the faster the resulting air movement.

This differential is made as great as possible in the updraft tower by 1) heating the air at ground level via a greenhouse with thermal storage, and 2) building the tower tall enough so that the ambient temperature of the air is naturally lower by a few degrees at the mouth.

A theoretical variation of the updraft tower replaces the tower with a controlled cyclonic atmospheric updraft vortex.

An inverse system is called a solar downdraft tower. This uses water vapor misted at the top of the tower, which causes the air to cool and fall down the tower through turbines.

Cross cut diagram of solar updraft tower
Image created by Robert Ferry based on a design by EnviroMission.

SOL TOWER

DESIGNERS
Tae Jung, Amit Vajaria, Pauline Sipin, Kevin Cheng, Yong Lee, Glenn Sanford, Javier Oliu

TECHNOLOGIES
solar updraft tower, thin-film photovoltaic, Vortex Bladeless™ wind turbine

ANNUAL CAPACITY
450 MWh

A submission to the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

SOLAR

SOLAR CHEMICAL

ARTIFICIAL PHOTOSYNTHESIS

Conversion efficiency is determined by the method used to convert hydrogen into mechanical or electrical energy.

Image via Wikimedia Commons.

ARTIFICIAL PHOTOSYNTHESIS

Some direct-to-hydrogen processes (PEC technology) are referred to as artificial photosynthesis, but they can also be more accurately described as photoelectrolysis.

There are other types of technologies that closely mimic photosynthesis by using carbon dioxide and water along with sunlight in order to produce hydrogen using ruthenium as a chlorophyll substitute. Other systems using cobalt oxide aim to create synthetic fuels such as methanol or methane.

Cyanobacteria (blue-green algae) can also be used to create hydrogen directly from sunlight, though the efficiency is lower.

Researchers Andreas Mershin and Shuguang Zhang of MIT's Center for Biomedical Engineering have shown how the actual molecules responsible for photosynthesis in plants (PS-I) can be inexpensively put to work in solar panels. Anyone could take grass clippings and, using a home kit, extract PS-I protein, mix it with a benign stabilizer, and paint the resulting goo onto any metal surface to generate a direct current. Work continues to increase efficiency (presently only 0.1%).

Photodimerization and photoisomerization are two other processes that are being investigated as methods of storing solar energy in usable forms.

Since the photosynthetic process removes CO_2 from the atmosphere, an efficient system in widespread commercial application could help to bring down atmospheric levels of CO_2 while at the same time producing clean energy.

SOLAR

EXPERIMENTAL SOLAR

EXPERIMENTAL SOLAR

Direct to Fuel or Sunlight to Petrol (S2P)

The Counter-Rotating-Ring Receiver Reactor Recuperator (CR5) at Sandia National Laboratories is demonstrating the conversion of solar energy directly into fuels such as ethanol that are combustible in existing gas engines without modification. The Sandia Solar to Petrol (S2P) system works by converting atmospheric CO_2 into oxygen and carbon monoxide which can then be converted into liquid fuels. Although combustion of the fuel that comes from this technology produces CO_2 as a by-product, the fuel is derived from the same quantity of atmospheric CO_2 and therefore a complete system can be seen as carbon neutral.

Molecular Solar Thermal (MOST)

Scientists at Chalmers University in Sweden and at UC Berkeley have discovered a molecule that is transformed into an energy-rich liquid isomer with the same atoms bound in a high-energy state when struck by sunlight. The energy in this isomer can be stored at room temperature and transported for up to 18 years. When the stored energy is desired for use a catalyst creates an exothermic reaction to warm the liquid above the boiling point of water, while allowing the low-energy molecule to be recycled for used again within the system.

Radiometer

Also called a light mill or a solar engine, the somewhat mysterious phenomenon of the radiometer has not been investigated as of yet for its potential to run electrical turbines, but perhaps the physics will be useful in the future.

Sunshine to petrol solar furnace
Image courtesy of Sandia National Laboratory.

WIND

HORIZONTAL AXIS WIND TURBINE (HAWT)

ONSHORE

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{wind power in}}$ = Varies with wind speed, typically up to 35%

ONSHORE HORIZONTAL AXIS WIND TURBINE

Perhaps the most commonly recognizable icon of the renewable energy industry, the horizontal axis wind turbine has come a long way from its historic origins milling grains and pumping water.

Early wind turbines typically had at least four blades, and sometimes many more. The first megawatt capacity turbine, built in Vermont in 1942, had only two large blades. There are some interesting modern examples of single-blade turbines as well. Standard contemporary utility-scale models typically have three blades and can have capacities as high as 12 megawatts.

The capacity of the modern HAWT is a function mostly of the overall outside diameter as measured from tip to tip, with some larger models exceeding 100 meters.

Smaller units can be designed to rotate with the assistance of a vane on the downwind side. Larger models must be turned more slowly by computer guided gears.

The energy available in the wind for conversion by a wind turbine is equal to $\frac{1}{2}\rho A v^3$ where ρ=air density, A=swept area of the rotor, and v=velocity of the wind.

In 1920, Albert Betz published the discovery (also made by Frederick Lanchester in 1915) that it is possible to extract 59.3% of the wind energy that passes through the swept area of the rotor. This is now known as the Betz limit.

The best free-running HAWTs are able to operate at 70% of the Betz limit, or at about 40% overall efficiency.

Wild Horse Wind Farm, Puget Sound Energy
Photo by Robert Ferry.

WIND

HORIZONTAL AXIS WIND TURBINE (HAWT)

OFFSHORE

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{wind power in}}$ = Up to 40%
Varies with wind speed, wind speed is more consistent offshore leading to greater overall output

OFFSHORE HORIZONTAL AXIS WIND TURBINE

There are two types of off-shore turbines—those mounted on pylons in shallow waters and those that are designed to float in deep water. Both types typically employ variations on the standard three-blade designs for the turbine itself.

Floating models can be designed to use this feature as a method of rotation to follow the wind direction. Also, floating models can take advantage of higher and more consistent wind speeds in the open ocean.

Floating HAWTs deal with the issue of aesthetics in that their location more than 12 miles from land makes them completely disappear beyond the horizon as viewed from shore.

Pylon-mounted shallow water turbines are less expensive and easier to maintain. Their power transmission lines are also shorter. The largest offshore turbine is 12 MW capacity (this number is consistently increasing), is 260 meters tall, and has three blades, each 107 meters in length.

HAWTs must be placed far apart from one another in order to minimize the shadow effect of air wake disturbance on the efficient operation of downwind turbines.

Offshore arrays can take advantage of the large open area of the sea to ensure the most proper placements and maximize overall efficiency.

Without topographic ground features to cause air disturbance, offshore installations also can take advantage of more consistent and higher velocity winds.

It is important to consider all possible impacts that offshore turbines can have on marine ecosystems.

Nysted Wind Farm (72 turbines, 165.6 MW capacity)
Image courtesy of Siemens AG, Munich/Berlin.

WIND

VERTICAL AXIS WIND TURBINE (VAWT)

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{wind power in}}$ = Varies with wind speed, typically up to 40%

VERTICAL AXIS WIND TURBINE (VAWT)

Vertical axis wind turbines are generally either Darrieus or Savonius in type (named after their early 20th century inventors).

A simple distinction is that Darrieus-type turbines use aerofoil blades and Savonius-type turbines use wind scoops. Gorlov helical turbine (GHT) is a variation on a standard Darrieus-type (invented by Professor Alexander M. Gorlov of Northeastern University in the 1990s).

Typically VAWTs have lower cut-in speeds (the wind speed at which they begin to produce electricity) than HAWTs and can be positioned lower to the ground than can HAWTs.

Another advantage of VAWTs is that they can be located in closer proximity to each other than can HAWTs. Some studies have shown that dense configurations can actually increase efficiency of the overall installation with turbines picking up wake energy from the rotations of adjacent turbines.

The earliest recorded use of wind power is with vertical axis wind turbines used to mill grains as long ago as 200 BCE. They were common in 7th century Persia and typically employed four vertical flags of fabric or woven grasses connected with wooden beams to a central column.

RevolutionAir WT1KW
(GHT type design)
Image courtesy of PRAMAC.
Design by Philippe Starck.

ROTOR

DESIGNERS
Louis Gadd, Aimee Goodwin, Danny Truong

TECHNOLOGIES
vertical axis wind turbines

ANNUAL CAPACITY
105 MWh

A submission to the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

CONCENTRATED WIND

COMPACT WIND ACCELERATION TURBINE (CWAT), ALSO KNOWN AS DIFFUSER AUGMENTED WIND (DAWT), OR DUCTED TURBINE

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{wind power in}}$ = 56%–90%
Varies with wind speed and depends on the size of the concentrator cone

CONCENTRATED WIND

This type of horizontal axis wind turbine uses a cone—or series of cones—to concentrate the wind before it hits the rotor. This increases the velocity of the wind as it passes through the rotor's swept area, and thus increase the efficiency of the overall system. They are also referred to as ducted turbines.

Ducted turbine manufacturers often refer to standard HAWTs as "free-running" turbines to distinguish the two types.

This technology has recently (after a long history of attempts) proven some measure of improvement over non-ducted HAWTs. The amount of material required to make the ducting cone is more than is required to extend the free-running blades to produce the same output. Due to this, their application to utility-scale installations may be limited, unless there is a secondary use for the ducting cone, for example a land art installation or buildings.

Comparison on wind energy conversion efficiency is often made between ducted and non-ducted rotor diameter. A more accurate comparison would be between non-ducted rotor diameter and the diameter of the ducted diffuser. In the former comparison, productivity is as high as 200%. Using the latter comparison, productivity is closer to 140%.

Illustration of a compact wind acceleration turbine.

FRESH HILLS

DESIGNERS
Designer: Matthew Rosenberg; Structural Engineering Consultant: Matt Melnyk; Production Assistants: Emmy Maruta, Robbie Eleazer

TECHNOLOGIES
WindTamer™, Carbon Dioxide Scrubber, SmartWrap™

ANNUAL CAPACITY
238 MWh

Second Place Winner of the 2012 Land Art Generator Initiative design competition for NYC, Freshkills Park—LAGI 2012.

HIGH ALTITUDE WIND POWER (HAWP) AND AIRBORNE WIND TURBINES (AWT)

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{wind power in}}$ = Up to 45%
Varies with wind speed
High altitude wind is very constant, leading to high annual energy output

WIND GRAZERS

DESIGNERS
Jennifer Sage, Peter Coombe, Andrew Kao, Allen Slamic, Taewook Cha, Trevor Sell, John Reed

TECHNOLOGIES
High altitude wind power

ANNUAL CAPACITY
525 MWh

A submission to the the 2012 Land Art Generator Initiative design competition for NYC, Freshkills Park—LAGI 2012.

HIGH ALTITUDE WIND POWER AND AIRBORNE

The power of the wind at high altitudes is much stronger and more consistent than what is typically available nearer to the ground. However, getting access to this excellent source of energy and harnessing it for electrical use presents obvious challenges.

HAWP has the potential to be a cheap and consistent source of energy. There are a wide number of HAWP technologies that are presently being developed. The electricity generation can either occur in the sky or at ground mooring, depending on the design type.

Some designs are derivative of kites or sails, whereby the conversion of energy is done at the ground level by harnessing the movement of a tether cable.

Airborne wind turbines (AWT)—use lighter-than-air blimps or balloons (aerostats) that rotate in the wind themselves (using the Magnus effect), or that create a duct and vane around a horizontal axis wind turbine as shown to the left.

Another design incorporates a glider designed to fly in a constant circle or figure-eight (e.g. Makani Power).

Douglas Selsam conceived of the ladder mill in 1977 to make use of high altitude winds. It is a series of kites arranged like a ladder in a loop formation. The shape of the individual kites changes based on their location in the loop so that they are either fully harnessing the wind or creating minimum drag resistance on their return journey.

Other HAWP designs include airfoils, airfoil matrices, spiral airfoils, drogues, kytoons (kite+ballooon), multiple-rotor complexes, fabric Jalbert-parafoil kites, uni-blade turbines, flipwings, tethers, bridles, string loops, and wafting blades.

UNWIND

DESIGNERS
David Donley, Michael Cinalli

TECHNOLOGIES
high altitude wind power
(kite HAWP)

ANNUAL CAPACITY
1,900 MWh

A submission to the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

VORTEX INDUCED VIBRATION RESONANT

WIND FOREST

DESIGNERS
Dalziel + Scullion, Qmulus Ltd., Yeadon Space Agency, and ZM Architecture

TECHNOLOGIES
Vortex Bladeless™ wind turbines

ANNUAL CAPACITY
900 MWh

Winning submission to LAGI Glasgow.

VORTEX INDUCED VIBRATION RESONANT WIND GENERATOR

The idea for this technology came to David Yáñez in 2012 after watching a video of the Tacoma Narrows Bridge oscillating in the wind. The Spanish startup he founded, Vortex Bladeless™, has developed turbines that harness the power of a phenomenon of vorticity called vortex shedding.

When wind passes across the body of the vertical cylindrical form, it shears away on the downwind side of the cylinder in a spinning whirlpool or vortex. The application of this phenomenon in a flowing stream of water can also be useful for energy production (see page 103).

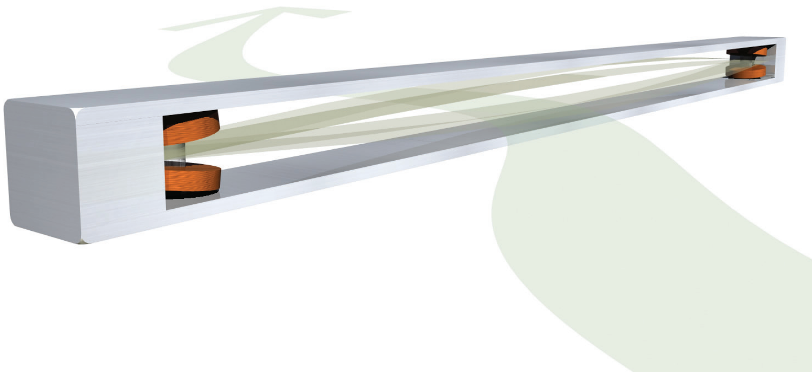
The vortex generated by the cylinder exerts a force on it, causing it to vibrate. The kinetic energy of the oscillating cylinder is converted into electricity using a linear alternator similar to those used to harness wave energy.

The design, which limits the number of moving parts and may therefore require less maintenance than conventional wind turbines, is currently in certification testing with a goal of market implementation that has shifted from 2018 to 2020 with the planned release of their Vortex Tacoma which will be 2.75 meters tall and have a nameplate capacity of 100 watts.

Testing points towards feasibility for urban installations although independent engineers have warned that there may be noise generated by the oscillations.

EMERGING WIND

The Windbelt works on the aerostatic flutter effect. Aerostatic flutter is created when a feedback loop occurs between an object's natural mode of vibration and an aerodynamic flow of energy passing over that object. The effect is similar to that of an aeolian harp which is used to create musical notes from the wind.



Example of a Windbelt in operation
Image made by LAGI based on design by Humdinger Wind Energy.

EMERGING WIND

Selsam Multirotor Wind Turbine

This invention by Douglas Selsam uses multiple rotors on a single drive shaft. There are two main variations on the technology. One type supports the system at a pylon located at about the midpoint of the driveshaft. The other type, called the "Sky Serpent," is supported from one end at the ground (location of the generator) and (like its name) is free to wave in the wind. It is supported at the other end by a balloon.

Vaneless Ion

This concept requires no moving parts and resembles a fence. Water mist with small differing charges allows wind to carry the charge between electrodes, producing electricity. It is similar in operational principal with Lord Kelvin's Thunderstorm where two bodies of water with small charge difference can create high voltage current by using the force of gravity. The vaneless ion generator uses the wind to move the water rather than gravity.

Windbelt

This type of wind generator uses a belt secured between two fixed points set within a rectangular housing. The belt oscillates rapidly creating a rocking motion at the two ends. This motion is harnessed by small kinetic energy generation devices employing magnets at the ends of the belt which move rapidly back and forth between metal coils.

Blade Tip Power

This wind turbine has the appearance of a horizontal axis wind turbine with a concentrator ring. However, with the blade tip design, the outside tips of the rotating blades carry the magnets that generate electrical current when they pass the copper coil banks on the inside of the perimeter ring.

GEOTHERMAL

CONVERSION EFFICIENCY = power out / thermal power in = 10%–25%
Natural steam is lower temperature than that produced by a boiler

GEOTHERMAL

Geothermal power harnesses natural thermal energy from deep underground deriving from residual heat from the formation of planet Earth and from heat that is constantly generated by radioactive decay.

The ability to harness the earth's geothermal energy is somewhat limited by site dependency (located near thermal plumes in the earth's crust), though recent technological advancements in drilling have extended the range. Advanced drilling technologies may have the potential to trigger seismic events by creating new fissures where tectonic pressure has built up over time.

The overall efficiency of the plant can be increased if exhaust heat from the turbine is captured and used for other purposes.

The earth's natural insulation and consistent year-round temperature can be used in any location as part of a ground source heat pump. This is a very useful energy conservation technology.

There are three geothermal power generation methods:

1. Dry steam: directly uses geothermal steam of 150 °C or greater to run turbines.
2. Flash steam: requires natural geothermal temperatures of 180 °C or more. High pressure steam is pulled into a low pressure separator which creates a powerful flash steam.
3. Binary cycle: can operate with water temperatures as low as 57 °C. This moderate heat is used to generate steam in a secondary fluid with a low boiling point.

Nesjavellir Geothermal Power Plant, Þingvellir, Iceland
Image courtesy of Gretar Ivarsson.

WATER

HYDROELECTRICITY

DAMMED RESERVOIR

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{power in}}$ = 80%–95% Turbine efficiency

Hoover Dam
Image via Wikimedia Commons.

DAMMED RESERVOIR

Conventional hydroelectricity uses dam structures to limit the flow of existing rivers. By selectively releasing water through turbines in the dam, the tremendous pressure of the water is converted to electrical energy.

There are many ecological side effects of interrupting the flow of existing rivers. This has led to the deconstruction of many hydroelectric dams and has resulted in a decrease in construction of new hydroelectric facilities.

The damming of a river causes the upstream side to flood large areas of land, disrupts fish spawning activities, and changes the characteristics (temperature, oxygen content, and silt content) of the downstream water.

Dams also come with the risk of structural failure and the resulting severe downstream flooding.

Generating approximately 16% of the world's electrical energy, hydroelectricity is by far the most established form of renewable energy.

It accounts for more than 71% of all renewable energy installed capacity (World Energy Council).

A long-term goal of the renewable energy transition might be to install enough wind and solar so that we can begin to decommission older dams and return rivers to their natural ecology.

Dammed reservoirs can also be useful as a type of energy storage (pumped-hydro), pumping water against gravity during times of high solar and wind production and releasing when demand exceeds supply.

WATER

HYDROELECTRICITY

RUN-OF-THE-RIVER (DAMLESS HYDRO)

CONVERSION EFFICIENCY = power out / power in = 80%–95% Turbine efficiency (limited by the amount of water that is diverted)

RUN-OF-THE-RIVER

While not entirely without ecological side effects, run-of-the-river type hydroelectricity plants offer an alternative to large reservoirs. In these installations only a portion of the river is diverted to the generators and the rest of the river is left to flow naturally.

Since no land is flooded, existing forests and natural habitats are not adversely affected.

With little storage capacity, this technology requires a river with a constant flow rate. While conventional hydro facilities can generate in the 10,000 MW capacity and above, run-of-the-river type plants typically are limited to around a 1,000 MW range or below.

In some installations a penstock pipe is placed in the river in order to regulate the flow of water. At the mouth of the penstock a constant water pressure is formed and is transferred to the turbine downstream.

Other installations simply place a water turbine in a strong current area of a river without any additional damming or piping. While this type of installation has the most minimal ecological impact, it is most susceptible to fluctuations in the flow rate of the river.

Fish ladder at the Columbia River John Day Dam
Image courtesy of the Army Corps of Engineers.

WATER

HYDROELECTRICITY

MICRO AND PICO HYDRO

CONVERSION EFFICIENCY = power out / power in = 50%–85% Smaller turbines are sometimes less efficient

MICRO AND PICO HYDROELECTRICITY

Classified as hydroelectric installations of less than 100 kW capacity for micro-hydro and less than 5 kW capacity for pico-hydro, these installations are in smaller rivers and streams. They can be either dammed reservoir type or run-of-the-river type but are usually the latter, especially for pico installations.

These types of installations are an excellent method of providing energy to small communities that do not have access to grid source power. Because the required output is small, the elevation drop (hydraulic head) of the water can be small, in some cases as little as one meter.

Pico-hydro can be very do-it-yourself and inexpensive. For example, Sam Redfield of the Appropriate Infrastructure Development Group (AIDG) has developed a pico-hydro generator that can be built for less than $150, made from PVC pipe, a modified Toyota alternator, and a five gallon bucket.

Many micro and pico-hydro installations use a penstock pipe to divert water from the natural flow of an existing river or stream.

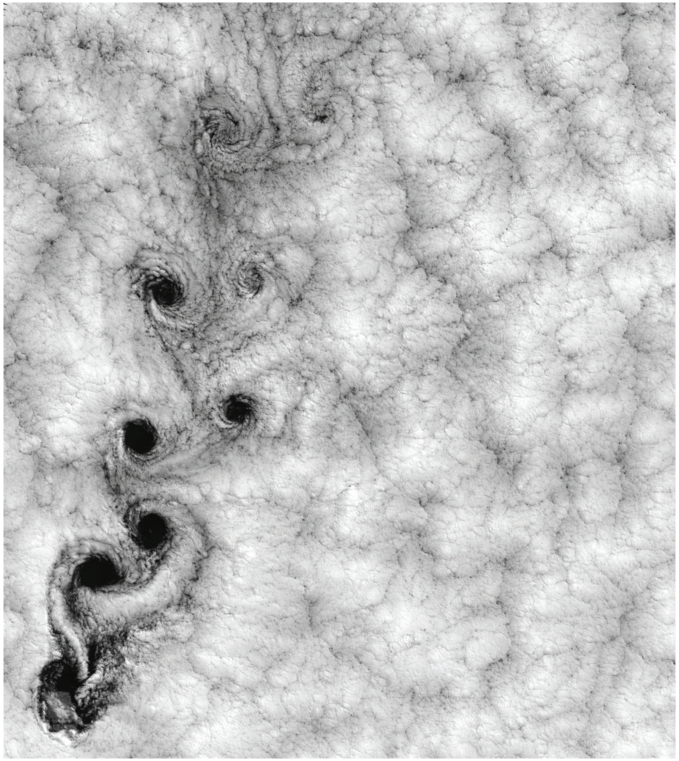
This pipe then flows to a small turbine generator, after which the water is channeled to rejoin the river at some point downstream.

Pico hydro project (Practical Action Sri Lanka) in Kalawana, Sri Lanka
Photo by Janani Balasubramaniam.

WATER

HYDROELECTRICITY (HYDROKINETIC)

VORTEX POWER



VORTEX HYDROELECTRICITY

When you place obstacles in the path of flowing water, it creates vortices or small turbulent spinning movements within the fluid. Recent research into harnessing these vortices has made some rapid progress. This is perhaps the hydro power least damaging to the environment since the installations are no more impactful to wildlife than natural obstacles along the path of water in a riverbed or ocean floor.

By placing fins in sequence, the vortex energy that is created by the wake of one fin is transferred to mechanical motion by the next fin downstream. This in turn generates a sustained feedback loop and maximizes the efficiency of the system. The vortex power converter functions in flowing water with a speed as slow as two knots.

Vortex Hydro Energy is a spin-off of the University of Michigan's Engineering Department and owns the rights to the VIVACE converter, which was invented in 2004 by Michael Bernitsas, a professor in the school's Department of Naval Architecture and Marine Engineering.

The VIVACE converter is inspired by the way that fish use water vortex energy to propel themselves.

Image of clouds off the Chilean coast near the Juan Fernandez Islands (von Karman vortex)
Image courtesy of NASA/GSFC/Landsat.

WATER

OCEAN TIDAL (HYDROKINETIC)

TIDAL STREAM GENERATOR (TSG)

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{power in}}$ = UP TO 40%

TIDAL STREAM GENERATOR

Similar to how a wind turbine harnesses the flowing kinetic energy of the wind, tidal stream generators harness the similar power of the water as tides flow in and out of coastal inlets by transferring the flow of the water to a rotating turbine. In outward appearance, they typically resemble a horizontal axis or vertical axis wind turbine. Since this is a relatively new technology, there are many approaches that are currently being tried and tested.

Tidal is an interesting form of energy. Whereas other forms of ocean energy (wave, thermal, ocean currents) can trace their energy origin to the wind or the sun, tidal energy is caused by the gravitational forces of the moon and the sun and the rotation of the earth. Depending on the body of water, tides can be either semidiurnal (two high waters and two low waters each day), or diurnal (one tidal cycle per day).

Five main types of TSG:

1. Axial: most similar to HAWT designs adapted to water application.
2. Vertical and Horizontal Axis Crossflow: similar to Darrieus-type VAWTs. They are often oriented horizontally in TSG applications.
3. Flow Augmented: uses a shroud to increase the flow to the turbine.
4. Oscillating: do not have a rotating component, but instead employ hydrofoil sections that move back and forth.
5. Venturi: a duct generates differential pressure which is used to run a turbine.

SeaGen tidal power plant, Strangford, County Down, Northern Ireland (blades raised for maintenance)
Image via Wikimedia Commons, user Ardfern.

WATER

OCEAN TIDAL (HYDROKINETIC)

BARRAGE

CONVERSION EFFICIENCY = power out / power in = UP TO 85%

BARRAGE TIDAL

Tidal barrage generators typically span the width of a tidal inlet or estuary and impede the entire tidal flow. Similar to dammed reservoir hydroelectricity in rivers, they can have negative effects on the marine ecosystems of the inlet due to the nearly complete separation of the estuary from the open ocean.

Changes to water salinity, water turbidity (opacity due to suspended solids), sediment disturbance, and fish kills in turbines also lead to negative environmental impacts. These effects can be mitigated with studied design strategies (the tidal lagoon type is the least damaging design), but there will always be greater impact from barrage-type tidal power than from TSG systems.

Five main types of barrage:

1. Ebb Generation: A natural tidal basin is filled through sluice gates until high tide. At low tide, gates are opened to run turbines.
2. Flood Generation: Turbines operate while the tide is rising.
3. Pumping: Excess grid power pumps additional water into the tidal basin (a variation on Ebb Generation).
4. Two Basin: An additional barrier wall across the basin provides nearly continuous generation.
5. Tidal Lagoon: A circular wall structure that has built-in basin(s). Surrounding water is free to flow around the lagoon.

Rance River Tidal Power Plant in Bretagne, France
Image via Wikimedia Commons, user Dani 7C3.

WATER

OCEAN MARINE CURRENT (HYDROKINETIC)

CONVERSION EFFICIENCY = power out / power in = UP TO 85%

OCEAN MARINE CURRENT

This type of ocean power would harness the streaming currents that exist in the world's oceans such as the powerful Gulf Stream in the Atlantic Ocean. These currents are so powerful that explorers sailing the Atlantic in the 16th century such as Ponce de León noted that often the stream of the water was more powerful than the wind, causing their ships to be still or even to move backward.

No installation has yet successfully been implemented to harness the oceans currents. While the available energy is quite vast, the difficulties for engineering systems in deep ocean water are also great.

Marine current energy is indirectly a form of solar power since the currents of the ocean are created by the heat energy of the sun.

There are three types of ocean marine current designs: seabed mounted systems, floating moored systems, and hybrid combinations of these two.

Seabed mounted systems can be designed with similar engineering to tidal stream generators, but must be located in relatively shallow waters where ocean currents are not at their strongest.

Floating moored systems offer the greatest energy potential but require engineering solutions to transmission and mooring.

Illustration of the Gulf Stream from Benjamin Franklin's *Philosophical and Miscellaneous Papers*, 1787
Image courtesy of Smithsonian Institute Libraries.

WATER

OCEAN WAVE ENERGY CONVERTER (WEC)

SURFACE FOLLOWING OR ATTENUATOR

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{power in}}$ = 70% Broad wave surface area

SURFACE FOLLOWING WAVE ENERGY GENERATOR

Wave energy converters (WEC) harness the local surface energy of large bodies of water.

If you think about it, wave energy is (indirectly) a form of solar energy. Waves are caused by the movement of wind over the surface of water, and the wind is caused by changes in air temperature created by the energy of the sun.

Waves travel immense distances with minimal energy loss. Because of this fact, the energy embodied in local waves is often out of phase with local wind conditions and can therefore act as a complement to off-shore wind power generation.

Surface following type wave generation uses long, hinged serpentine devices that create pressure in chambers of oil as the segments of the device change their orientations with the action of the waves. The release of the oil pressure drives hydraulic motors within the floating machine.

In 2004 Pelamis Wave Power first transmitted electricity to the land grid. Each Pelamis machine is currently rated at 750 kW.

Second generation P2 Pelamis machine in operation at the European Marine Energy Centre (EMEC) in Orkney
Owned by E.ON UK. Image courtesy of Pelamis Wave Power Ltd.

WATER

OCEAN WAVE ENERGY CONVERTER (WEC)

BUOY OR POINT ABSORBER

CONVERSION EFFICIENCY = power out / power in = 80%
Limited wave surface area

Buoy type WEC off the coast of Hawaii
Image courtesy of Ocean Power Technologies, Inc.

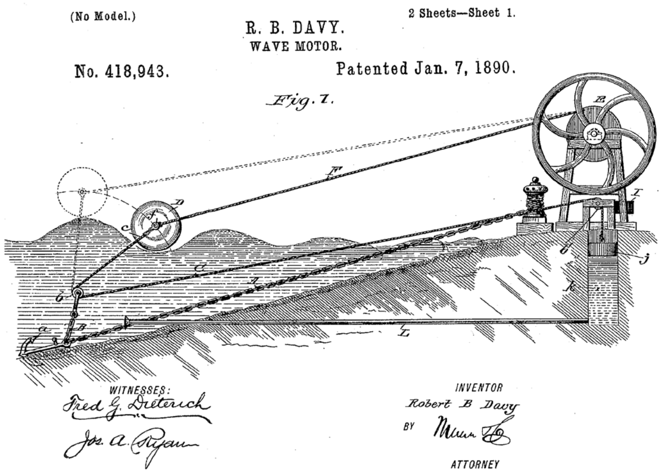
POINT ABSORBER WAVE ENERGY GENERATOR

Buoy type wave energy converters (WEC) use the up and down motion of the waves at a single point. The rocking motion moves liquids between chambers to spin turbines.

In more shallow conditions a piston can extend to the sea floor to drive a hydraulic motor, a linear generator, or to fill compressed air chambers that run small internal air turbines.

Deeper water provides longer period waves and more regular wave energy without as much potential for damage to equipment from cresting waves. But the logistics of electrical transmission and equipment maintenance must be weighed against this.

There have been attempts made to harness wave energy since the late 19th century. The ocean is a corrosive and harsh environment for the continuous operation of mechanical devices.



CATCHING THE WAVE

DESIGNERS
Christina Vannelli, Liz Davidson, Matthew Madigan

TECHNOLOGIES
point absorber wave energy converter (similar to CETO™ by Carnegie Wave Energy)

ANNUAL CAPACITY
16,000 MWh

A submission to the 2016 Land Art Generator Initiative design competition for Santa Monica—LAGI 2016.

OCEAN WAVE ENERGY CONVERTER (WEC)

OTHER TYPES

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{power in}}$ = UP TO 85%

Oyster wave energy converter (oscillating wave surge type) 800 kW
Image courtesy of SSE and Aquamarine Power.

OTHER WAVE ENERGY GENERATORS

Oscillating Wave Surge Converter

The oscillating wave surge energy converter is installed in nearshore locations of approximately 10 meters depth and is secured to the seabed. A mechanical flap at the surface is hinged to allow it to move with the waves. This movement drives hydraulic pistons that create high pressure water. The pressure from the pistons drives a constant flow through a series of pipes to the shore where the pressurized water runs a turbine to generate electricity.

Wing Reflector or Overtopping

A floating reservoir is set at a higher elevation than the surrounding ocean wave troughs. The crests of the waves gradually fill this reservoir by overtopping the sides. The reservoir, once filled, releases the water back into the ocean to run a series of low head hydraulic turbines. The device is designed to be heavy for stability against rolling and is constructed with thick ship-like steel plates. It is slack moored to the seabed to anchor it permanently in place.

Oscillating Water Column (OWC)

Installed at the shoreline, a concrete enclosed chamber of air is compressed and suctioned as the waves at the bottom of the chamber rise and fall. Wells turbines (developed by Alan Arthur Wells in the late 1970s)—which rotate continuously in one direction regardless of direction of air flow—convert the kinetic energy of the waves into electricity.

Energy conversion technologies used in wave energy converters include hydraulic ram, elastomeric hose pump, pump-to-shore, hydraulic turbine, air compression with wind turbine, and direct linear generator.

NOCTILUCALES

DESIGNERS
Ricardo Avella, Andrés Tabora, Michael Henriksen, Carla Betancourt, Silvia Mercader, Laura Vera, Oriana De Lucia, Martin Von Bülow, Laura Vivas, Miguel Rosas

TECHNOLOGIES
wave energy converter (by WavePiston™), reverse osmosis desalination

ANNUAL CAPACITY
4,200 MWh (less the energy used for desalination), 14 million liters of drinking water per year

A submission to the 2016 Land Art Generator Initiative design competition for Santa Monica—LAGI 2016.

WATER

OCEAN

OSMOTIC POWER
OR SALINITY GRADIENT POWER

OSMOTIC POWER

In locations where freshwater mixes with saltwater there is an opportunity to take advantage of an interesting characteristic of water which is its strong tendency towards equalization of salinity levels. Therefore, if two containers of water are separated by a semi-permeable membrane, water will pass from the freshwater side to the saltwater side thus increasing the pressure on the saltwater side. This increased pressure can then be released to turn a turbine and generate electricity in a continuous cycle.

Methods of energy conversion include: pressure-retarded osmosis (used in commercial production), reversed electrodialysis (experimental), and capacitive (experimental).

These methods could theoretically be applied in combination with a solar pond (see page 3) where salinity gradients exist between water layers within the pond.

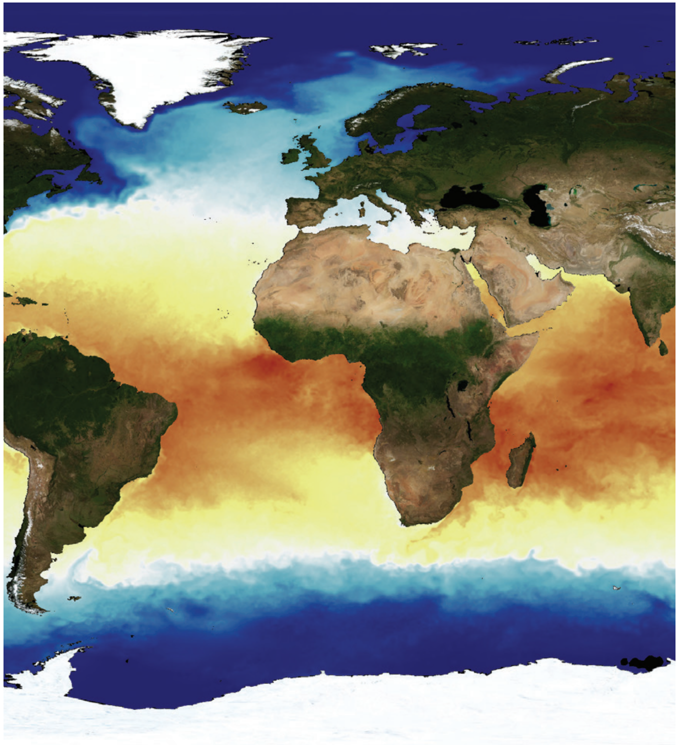
The Norwegian company Statkraft opened the world's first facility for osmotic power generation in 2009 with a limited capacity of 4 kW, using the technology of pressure-retarded osmosis.

The negative environmental impacts of discharging brackish water (by-product of osmotic power) in large quantities into surrounding waters should be carefully mitigated.

Osmotic membranes are coiled inside pressure vessels
Photo courtesy of Statkraft.

OCEAN THERMAL ENERGY CONVERSION (OTEC)

CONVERSION EFFICIENCY = $\frac{\text{power out}}{\text{power in}}$ = 10%



OCEAN THERMAL ENERGY CONVERSION

Water in the deep ocean is many degrees cooler than surface temperature water. The difference in temperature can be used to run a heat engine either using the water itself in an open-loop (placing warm ocean water in a low pressure system causes it to boil), or by transferring the heat energy to a closed-loop system with a heat exchanger and a low-boiling point liquid such as ammonia.

The technology for energy conversion is similar to that employed in solar pond systems (see page 3), such as Rankine cycle low pressure turbines.

Cool deep water from oceans or deep lakes (typically at a constant 4 °C or 40 °F) can also be used as heat sinks, reducing the demand side electrical loads of buildings that are sited to take advantage of this. A similar (though less efficient) effect can be utilized in almost any location via ground source heat sink loops.

OTEC can also supply quantities of cold water which can be used for air conditioning and refrigeration.

Some open-loop OTEC designs can also create desalinated water as a by-product.

Satellite composite showing ocean thermal energy
Image courtesy of the National Oceanic and Atmospheric Administration.

WATER

OTHER HYDROKINETIC ENERGY TECHNOLOGIES

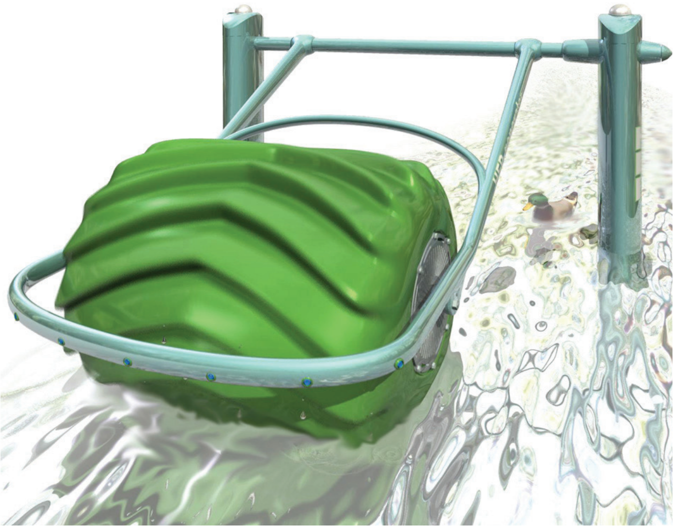


Image created by Paul Price and used with permission of HEB.

OTHER HYDROKINETIC ENERGY TECHNOLOGIES

Dynamic Tidal Power (DTP)

DTP is an untested technology that could theoretically produce large amounts of power in the range of 10,000 MW capacity by creating extremely large artificial jetties into the ocean that would be shaped like a "T" as viewed from the sky.

The top of the "T" would serve to separate tidal action on either side of the long leg that connects to the land. Computer simulation models have shown that the length of the system would have to be in the area of 30 km to be viable, which would require an extremely large capital expense. There may be negative impacts to marine habitat by building such an extensive structure out into the ocean.

Hydroelectric Barrel (HEB)

Mike Lowery has developed a floating waterwheel that spins on the surface of a river or stream. The treading of the outer surface keeps the barrel from sinking (counteracts the Coanda effect).

Gravitational Water Vortex

Vortex gravity turbines are placed within a water channel and use a controlled vortex to run a turbine. You can see the physics behind this system by watching water as it flows down your tub drain. A vertical axis turbine is placed in the center of a similar (much larger) swirling funnel and rotates to generate energy. The system can be installed run-of-the-river (and is therefore lower impact to the environment) by channeling some of the water to the turbine and then back to the river. The technique has been developed separately by both Paul Kouris and Franz Zotlöterer.

BIO

Conversion efficiency is determined by the method used to convert the biomass into mechanical or electrical energy

NATURAL SOLIDS

Biomass is considered a sustainable energy resource because it is a product of organic processes which naturally regenerate at a rapid cycle (as opposed to fossil fuel energy sources which take millions of years to form naturally). Biomass can be combusted directly as a solid fuel or converted to liquid or gas biofuels that can be used in either a combustion engine (conversion to mechanical energy) or in a fuel cell (conversion to electrical energy).

The natural solids biomass category includes the combustion of any renewable solid organic material such as wood or charcoal. While technically a renewable energy source, the combustion of solid biomass contributes heavily to greenhouse gases and the harvesting of wood for this purpose increases deforestation.

Conversion to mechanical, heat, or electrical energy is generally inefficient, and the environmental and human health costs are too high for biomass energy to be used on a large scale.

Solid biomass was the predominant form of energy prior to the advent of coal mining. This transition began to occur in the late medieval period (around 1500) in Europe, when unsustainable use of wood as fuel had resulted in massive deforestation.

***Important Note**
The by-products of solid biofuel combustion are very hazardous to human health and include high quantities of the greenhouse gases that are directly responsible for global climate change.

A strong reliance on solid biomass energy in the low carbon world is responsible for highly elevated rates of respiratory diseases, especially among women who are exposed to the toxic fumes for extended periods every day during cooking activities.

GOLDEN ROOTS

DESIGNERS
Ronny Zschörper,
Franziska Adler

TECHNOLOGIES
biomass, piezoelectric paving

ANNUAL CAPACITY
52 MWh

A submission to the 2014 Land Art Generator Initiative design competition for Copenhagen—LAGI 2014.

BIO

BIOMASS AND BIOFUEL

BIOGAS AND LANDFILL GAS

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy

BIOGAS AND LANDFILL GAS

Biogas is created through the breakdown of any organic material (biomass) in an oxygen-poor environment. The resulting gas by-product is mostly methane and carbon dioxide. Biogas is similar in composition to conventional natural gas and as such can be compressed or fed into a municipal gas grid. It can be used for many different purposes including cooking, heating, lighting, transportation, and electricity production.

It can be either tapped from the underground activity in a landfill site, or it can be produced in specially constructed anaerobic digester tanks.

Farms with such tanks can process manure into biogas, reducing the amount of nitrous dioxide and methane that would otherwise enter the atmosphere. These two gases have a far greater atmospheric warming effect than does carbon dioxide (nitrous dioxide = 310 times greater, and methane = 21 times greater).

BIO

Landfill gas infrastructure at Freshkills Park, the former Fresh Kills Landfill, New York City
Photo by Robert Ferry.

BIO

BIOMASS AND BIOFUEL

WASTE TO ENERGY (WTE)

Conversion efficiency is determined by the method used to convert the biochar into mechanical or electrical energy

WASTE TO ENERGY

WtE is the use of nearly any kind of waste for combustion (incineration) to generate electricity, or for processing into methane or similar fuel.

WtE technologies that do not require incineration include gasification (produces hydrogen and synthetic fuels), thermal depolymerization (produces synthetic crude oil), pyrolysis (produces combustible tar, bio-oil, and biochars), plasma gasification (PGP) (produces syngas). Other technologies to convert waste materials do not require incineration or the input of external heat. These include anaerobic digestion (produces biogas rich in methane), fermentation production (produces ethanol, lactic acid, hydrogen), and mechanical biological treatment (MBT).

For incinerators, limestone scrubbers can greatly reduce the emission of harmful chemicals from incineration, and while there is CO_2 released, the emissions are less environmentally toxic than the greenhouse gases and leachate that are produced by landfills even if some of that landfill gas is captured.

WtE is nearly always preferable to landfill waste disposal especially when the plant uses combined heat and power (providing industrial heat or district heating in addition to electricity). Given the mixed track record of plastic recycling and the energy that goes into that process, the argument can be made that well-scrubbed WtE is a better alternative for many plastics than recycling.

The world's two most interesting WtE power plants are one in Vienna, Austria designed by Friedensreich Hundertwasser and one in Copenhagen by Bjarke Ingels Group, which doubles as a ski slope.

Trezzo sull'Adda 3 Waste to Energy Plant in Milan, Italy
Image courtesy of Falck Renewables SpA.

BIO

BIOMASS AND BIOFUEL
ALCOHOL BIOFUEL
ETHANOL

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy

ETHANOL

Alcohol biofuels like ethanol are produced through the fermentation of sugars from high carbohydrate content plants such as corn, potato, beet, wheat, or sugarcane.

Other (more costly) processes can use wood product waste and fibrous grasses such as switchgrass that grow very quickly.

Ethanol can be used as an additive to gasoline or it can be used in a majority ethanol mix such as "E-85" (ethanol 85%) in engines that have been appropriately modified.

Some concerns over the proliferation of "first generation" ethanol type biofuels include:

Food vs. Fuel: with the world frequently experiencing food shortages and people suffering from starvation, it is not wise to convert useful food resources into fuels if other alternatives are available. Ethanol use has been promoted by the agricultural industry lobby because higher corn prices result from increased demand.

Conventional oil price deflation: the abundant use of biofuels has kept oil prices below where they would otherwise be. Some estimates put the deflation at as much as 25%. The price deflation of oil may contribute to a greater and longer lasting reliance on conventional fossil fuels.

Loss of biodiversity and deforestation: with more demand for sugarcane and high sugar corn, vast fields are dedicated to monoculture crops.

Pollution: the combustion of ethanol produces carcinogenic by-products such as formaldehyde and acetaldehyde.

Water: crops that most easily produce the best performing biofuels require significant irrigation resources.

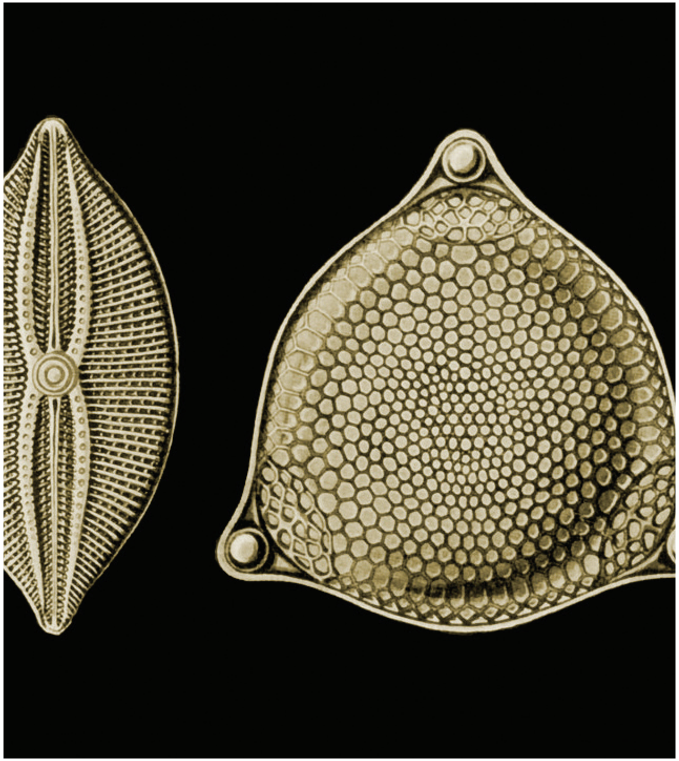
As a response to these issues, new methods have evolved as second, third, and fourth generation biofuel technologies.

BIO

BIOMASS AND BIOFUEL
ALGAE BIOFUEL

METHANE, ETHANOL, BIODIESEL, BIOBUTANOL, SOLALGAL FUEL

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy



ALGAE BIOFUEL

Butanol can be used in gasoline engines without engine modification. The exact same fuel can be produced from fossil fuels or from biomass. Biobutanol is the kind made from biomass. It can be used in a variety of engines and can even be used as jet fuel!

The process is similar to the way that ethanol can be formed via (anaerobic) fermentation processes. Butanol production uses a specialized bacteria, Clostridium acetobutylicum, instead of yeast.

Clostridium acetobutylicum is also known as the Weizmann organism. Chaim Weizmann first used this bacteria in 1916 for the production of acetone from starch. Butanol was a large by-product of this fermentation (twice as much butanol was produced as was acetone).

The process also creates a recoverable amount of hydrogen and a number of other by-products: lactic and propionic acids, acetic, isopropanol, and ethanol.

Diatoms or algae can be used as the raw organic material (feedstock) for butanol production instead of agricultural crops like corn or sugar cane.

The biobutanol conversion process can be powered (catalyzed) entirely by solar energy.

When algae is used as the feedstock and solar power as the energy source, the resultant biobutanol from this process is known as Solalgal fuel.

Drawing of diatoms
From Ernst Haeckel's *Kunstformen der Natur* (Artforms of Nature), 1904.

GRID SLIDE

DESIGNERS
Morten Rask Madsen, Julie Trier Brøgger, Julie Rindung, Natalia Guerrero Gutiérrez, Artis Kurps, Kevin Bailey, Søren Laurentius Nielsen, Per Møller, Jesper Ahrenfeldt, Tobias Thomsen

TECHNOLOGIES
algae biofuel

ANNUAL CAPACITY
100,000 MWh

A submission to the 2014 Land Art Generator Initiative design competition for Copenhagen—LAGI 2014.

BIO

BIOMASS AND BIOFUEL

BIODIESEL

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy

BIODIESEL

Using a process known as transesterification, naturally occurring oils or fats (biolipids) are transformed into liquid diesel fuel that can be used in most diesel engines. The raw material, or feedstock, can be animal fat, vegetable oil, soy, rapeseed, jatropha, mahua, mustard, flax, sunflower, palm, hemp, field pennycress, Pongamia pinnata, or algae.

The specific chemical process (type of transesterification) when applied to biodiesel production is called methanolysis. It requires the addition of alcohol to the biolipid in the presence of an acid or base catalyst. While complicated chemically, the process does not require added heat. The same process can be used for plastic recycling.

The process of methanolysis that creates biodiesel fuel from biomass has its origins in experiments to produce glycerine for explosives during World War II.

The chemical processes that go into transesterification, and the reliance on the availability of glycerol, sodium hydroxide, and other compounds make this type of biodiesel production relatively expensive.

Producing biodiesel at a large scale would place a burden on land use similar to the problems created by ethanol production. If diverse natural ecosystems such as grasslands or forests are burned to allow for more biodiesel from soybean production for example, then the impact of biodiesel is a net increase in carbon in the atmosphere. There is evidence that the Renewable Fuel Standard (RFS) in the United States has led directly to deforestation in other parts of the world.

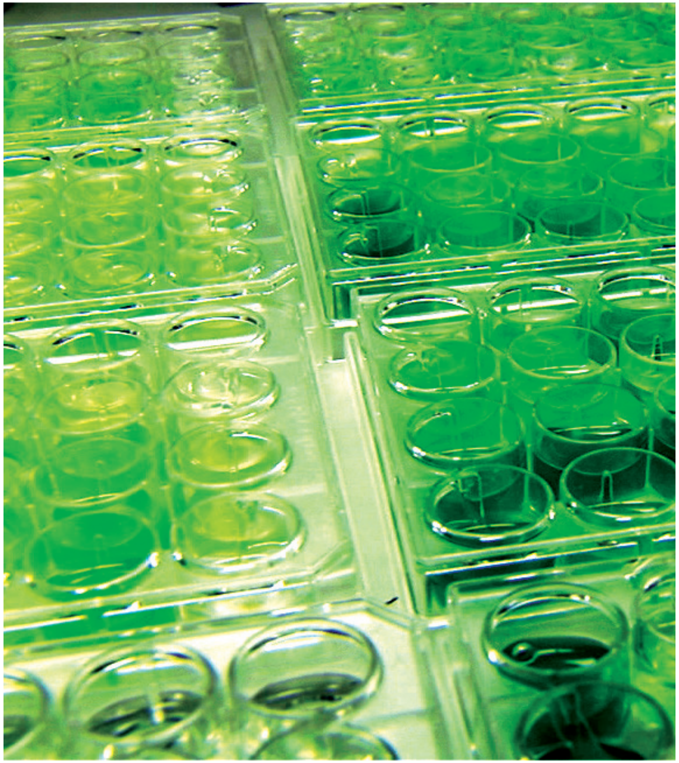
A Sunflower field in Fargo, North Dakota
Image courtesy of the Agricultural Research Service of the US Department of Agriculture.

BIO

BIOMASS AND BIOFUEL

GREEN DIESEL OR RENEWABLE DIESEL

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy



GREEN DIESEL

Green diesel uses naturally occurring oils (biolipids) to produce diesel fuel. Natural oils can be extracted from canola, algae, jatropha, salicornia, or tallow. It differs from biodiesel in that it uses traditional fractional distillation methods (similar to those used in the production of petroleum diesel) to process the oils rather than through transesterification.

The benefit of algae cultivation as feedstock is that it can be produced using ocean water or wastewater (it does not require freshwater resources) and that it is biodegradable and relatively harmless to the environment if spilled. Algae costs somewhat more to produce per unit of feedstock mass (compared to soybean) due to the complexity of cultivation, but it can be converted into much more fuel energy per unit of feedstock mass, which more than makes up for this difference. Cultivation can also occur in the ocean, where it does not compete with conventional agriculture or lead to deforestation.

The fractional distillation process required to produce green diesel from biolipid feedstock requires heating the feedstock to very high temperatures (approximately 600 °C). This is usually done by combusting fossil fuels, but solar thermal systems could potentially fill the need instead. The vaporized feedstock rises up a distillation column where it is separated into its constituent parts and cooled for use.

This type of green diesel should not be confused with fossil-fuel based diesel that has been dyed green to distinguish its quality.

Algae growing in Susan Golden's lab at UC San Diego
Image courtesy of UC San Diego.

BIO

BIOMASS AND BIOFUEL

SYNGAS

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy

SYNGAS

Syngas is a mixture of carbon monoxide and hydrogen that is created by partially combusting (in a medium-low oxygen environment) any material rich in carbon content including biomass and even plastic waste. It can also be produced by coal gasification, but that method is non-renewable and carbon emissions intense.

The name "syngas" comes from its use as an intermediate in the production of synthetic natural gas (SNG) and for producing ammonia or methanol. Syngas can also be used as an intermediate in producing synthetic petroleum for use as a fuel or lubricant. The use of syngas for the production of natural gas or synthetic petroleum fuel is accomplished by way of a technique known as the Fischer–Tropsch process.

Syngas production has been shown to be possible using solar energy as the single source of heat in the process.

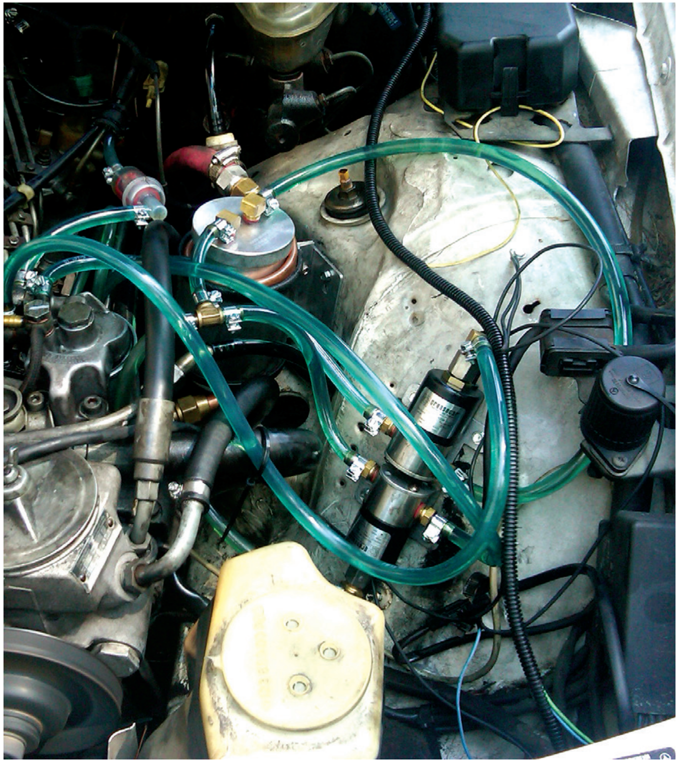
Syngas is combustible and can be used in internal combustion engines, but it contains less energy density than natural gas.

BIO

BIOMASS AND BIOFUEL

VEGETABLE OIL

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy



Waste vegetable oil conversion
Image courtesy of Dr. Dave's Automotive.

VEGETABLE OIL

Vegetable oil can be used in some older diesel engines or in newer engines that are modified. Modifications typically incorporate systems to preheat the oil to allow for proper atomization of the fuel.

In many cases, there is a greater wear and tear on the engine parts from 100% vegetable oil use due to its high viscosity. This can be mitigated by burning conventional diesel at the beginning and the end of the cycle and/or by mixing the vegetable oil with conventional diesel.

Vegetable oil can also be blended with gasoline, diesel, or kerosene, to reduce viscosity, but this has had generally poor results in sustained practical use.

Vegetable oil used as fuel can be either waste vegetable oil (WVO) left over from its first use such as food frying, or it can be straight vegetable oil (SVO) also known as pure plant oil (PPO).

BIO

BIOMASS AND BIOFUEL

HYDROCARBON PLANTS AND BIOGASOLINE

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy

HYDROCARBON PLANTS AND BIOGASOLINE

Hydrocarbon plants, such as Euphorbia lathyris and Euphorbia tirucalli, produce terpenoids in sufficient quantities through their metabolic processes that it is possible to convert them directly into gasoline-like fuels.

Biogasoline is usually produced from algae using complex industrial conversion processes such as deoxygenation/reforming or hydrotreating. The resulting fuel is very similar to conventional gasoline but with higher octane levels. It is not an alcohol fuel like ethanol.

A list of hydrocarbon plant families:

- Euphorbiaceae
- Apocynaceae
- Asclepiadaceae
- Sapotaceae
- Moraceae
- Dipterocarpaceae
- Compositae (sunflower)
- Leguminosae

Some algae also produce hydrocarbons.

Dr. M. Calvin (1979) was the first to collect the hydrocarbons from plants of the Euphorbiaceae family.

Euphorbium resinifera (Euphorbiaceae)
Image from Franz Eugen Köhler's Medizinal-Pflanzen, 1887.

BIO

BIOMASS AND BIOFUEL

PYROLYSIS AND BIOCHAR DERIVED FUELS

Conversion efficiency is determined by the method used to convert the biochar into mechanical or electrical energy

PYROLYSIS AND BIOCHAR

Pyrolysis is a high temperature and high pressure thermochemical decomposition process that differs from anaerobic digestion or fermentation and requires very little water.

The process requires pressure and temperatures of over 430 °C in an oxygen-free environment. It can be used in controlled conditions and with biomass feedstock to produce solid biochar, along with bio-oils, which resemble light crude oil, and syngas.

Flash pyrolysis, in which feedstock is heated quickly for two seconds to between 350 °C and 500 °C, is the most efficient method.

Pyrolysis can also be used to create biochar from organic waste and charcoal from wood feedstock. Biochar is useful as a fertilizer, increasing soil fertility and sequestering carbon in soils. When combusted for heat, biochar solids burn cleaner and put off more consistent heat than wood.

Pyrolysis is the same process that occurs when you roast vegetables, bake a pie, or grill a cheese sandwich. In dry conditions, the carbohydrates present on the surface of these foods undergo pyrolysis and leave behind the darkened brown crust or black residue of charcoal. Controlled pyrolysis of sugar (170 °C) results in caramel.

Pyrolysis is a different process than combustion, occurring generally below ignition temperature.

Biochar research at Uppsala University
Photo by Tor Kihlberg.

BIO

MICROBIAL FUEL CELLS (MFC)

Conversion efficiency is determined by the method used to convert the biofuel into mechanical or electrical energy

MICROBIAL FUEL CELLS

The idea of using microbial cells in an attempt to produce electricity was first conceived at the turn of the 19th century. M.C. Potter was the first to perform work on the subject in 1911.

Microbial fuel cells produce electricity by harnessing the natural bio-electrical systems that convert chemical energy into electrical energy in anaerobic microbial ecosystems.

There are two types of MFC:

Mediator Microbial Fuel Cell

Most of the microbial cells are electrochemically inactive. The electron transfer from microbial cells to the electrode is facilitated by mediators such as thionine, methyl viologen, methyl blue, etc., which are expensive and toxic.

Mediator-free Microbial Fuel Cell (Plant-MFC)

Mediator-free microbial fuel cells do not require a mediator but use electrochemically active bacteria to transfer electrons to the electrode. Mediator-less microbial fuel cells can run on greywater and derive energy directly from certain aquatic plants.

The University of Queensland, Australia, completed a prototype MFC in partnership with Foster's Brewing. The prototype converts brewery wastewater into carbon dioxide, clean water, and 2 kW of power.

Plant-e (spin off company from Wageningen University) and designer Ermi van Oers have developed the Living Light, a mediator-free system that can be installed in landscapes or interior spaces.

Living Light by Plant-e and Ermi van Oers
Image courtesy of Living Light.
www.livinglight.info
www.novainnova.com

BIO

LIGHT UP

DESIGNERS
Martin Heide, Dean Boothroyd, Emily Van Monger, David Allouf, Takasumi Inoue, Liam Oxlade, Michael Strack, Richard Le (NH Architecture); Mike Rainbow, Jan Talacko (Ark Resources); John Bahoric (John Bahoric Design); Bryan Chung, Chea Yuen Yeow Chong, Anna Lee, Amelie Noren (RMIT students)

TECHNOLOGIES
flexible mono-crystalline silicon photovoltaic, wind energy harvesting, microbial fuel cells

ANNUAL CAPACITY
2,220 MWh

First Place Winner of the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

OTHER

PIEZOELECTRIC GENERATOR

PIEZOELECTRIC

The piezoelectric effect was discovered by Jacques and Pierre Curie in 1880. Piezoelectric generators convert mechanical strain into electrical energy by taking advantage of the material property of piezoelectric materials. The name comes from the Greek word piezein, which means to press or squeeze.

Electric charge accumulates in certain types of solid materials when mechanical stress or pressure is applied. Naturally occurring piezoelectric materials include crystals (such as quartz, sucrose, and topaz), wood, bone, DNA, silk, enamel, and dentin. Synthetic ceramic and crystal materials, called ferroelectrics exhibit piezoelectric constants far greater than natural materials. Some examples include barium titanate, lead zirconate titanate, and bismuth ferrite.

Piezoelectric generators can be inserted into shoes or in walkway pavers to harvest the energy of walking, jumping, or dancing. Piezoelectric generators can also be used to harvest wind energy, vibrations, sound waves, or any other kind of kinetic energy.

The piezoelectric effect operates in both directions. Therefore a piezoelectric material will bend or deform when electricity is applied to it (the converse piezoelectric effect). This is useful in actuators that require very precise movement.

Common applications of piezoelectric materials include igniters, quartz watches, and pickup amplifiers for guitars.

Pavegen Systems paver in a London sidewalk
Image courtesy of Pavegen Systems Ltd.

SUPER CLOUD

DESIGNERS
Lucas Jarry, Rita Serra e Silva, Lucas Guyon, Marianne Ullmann

TECHNOLOGIES
piezoelectric discs

ANNUAL CAPACITY
2,487 MWh

A submission to the 2014 Land Art Generator Initiative design competition for Copenhagen—LAGI 2014.

OTHER

TRIBOELECTRIC

DREAMTIME

DESIGNERS
Kyle Taveira

TECHNOLOGIES
triboelectric energy harvesting fabric, piezoelectric stack actuators

ANNUAL CAPACITY
100 MWh

A submission to the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

TRIBOELECTRIC

The triboelectric effect describes the production of electrical charge when a material of one kind is placed in frictional contact with a material of a different kind.

Commonly referred to as "static electricity" the effect can be seen when drawing a plastic comb through hair, or moving a rubber balloon against a shaggy carpet.

Triboelectric nanogenerators (TENG) produce electricity by taking advantage of the electrostatic properties of different materials. Kinetic energy moves the two different materials together and apart and this movement sends a flow of electrons that can be distributed for use, or stored in a battery.

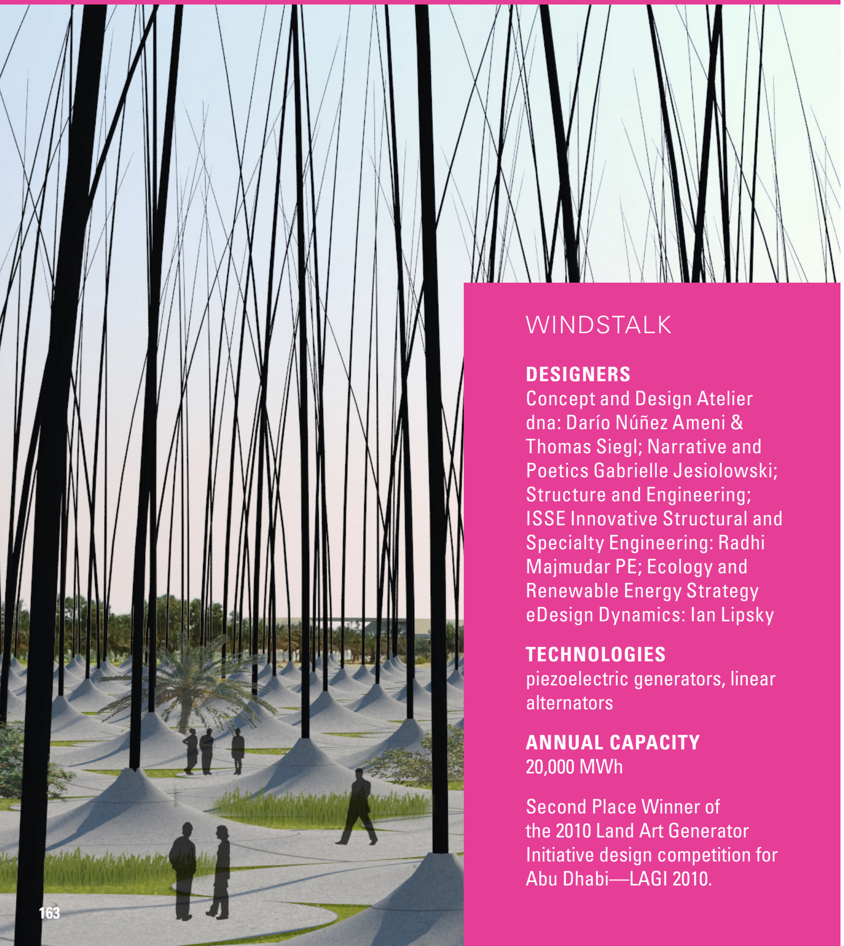
Triboelectric nanogenerators are a relatively new kind of energy harvesting technology developed by Professor Zhong Lin Wang and his team at Georgia Institute of Technology in 2012. It uses the triboelectric effect combined with electrostatic induction.

Since then, many universities have been working on increasing the energy density and productivity of TENG.

The technology has the potential to generate between 50 and 300 watts per square meter by harnessing the kinetic energy of wind, waves, or the movement of people.

OTHER

ENERGY HARVESTING



WINDSTALK

DESIGNERS
Concept and Design Atelier dna: Darío Núñez Ameni & Thomas Siegl; Narrative and Poetics Gabrielle Jesiolowski; Structure and Engineering; ISSE Innovative Structural and Specialty Engineering: Radhi Majmudar PE; Ecology and Renewable Energy Strategy eDesign Dynamics: Ian Lipsky

TECHNOLOGIES
piezoelectric generators, linear alternators

ANNUAL CAPACITY
20,000 MWh

Second Place Winner of the 2010 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2010.

ENERGY HARVESTING

There are many ways that kinetic, heat, and other energy (natural or man-made) can be harvested and converted to electrical energy.

Alternators and Dynamos convert rotational or linear motion into electricity through electromagnetic induction. Anything in the world with a consistent movement can be connected to a generator to make electricity. Kinetic energy can be found in winds and breezes, human activity, water movement, and the expansion and contraction of materials.

Ambient Radiation from radio transmitters can be collected and converted to electricity.

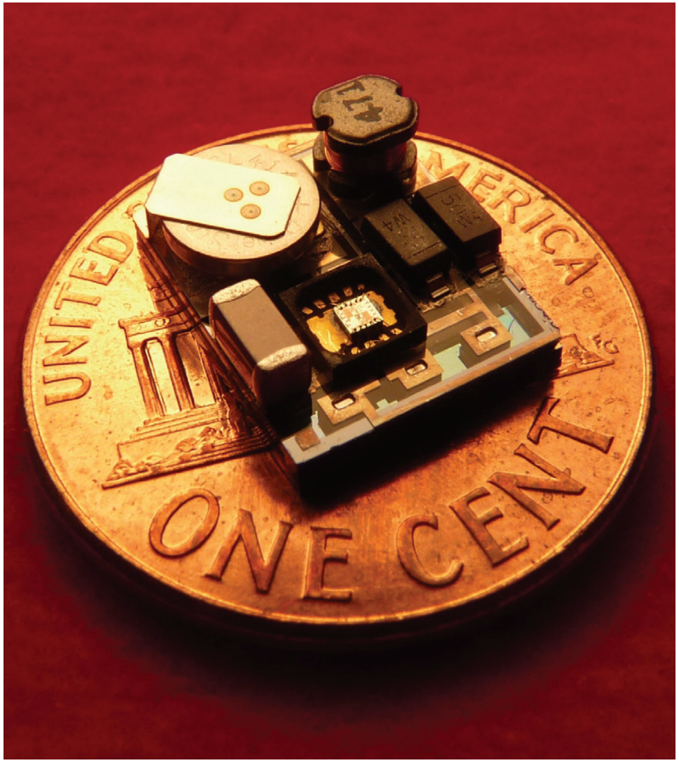
Thermoelectric Generators (TEG) can harness heat energy from the sun and convert it directly into electricity by utilizing the Seebeck effect (see page 65). They can also be used to harvest heat energy from other sources such as industrial processes that would otherwise be wasted. They can even harness energy from buildings at night and from the heat of a human body.

Pyroelectric Materials convert temperature change to electricity and can do so at much higher temperatures than TEG materials.

Electrostatic converters turn vibration energy into electricity. The vibration of the device moves plates of charged variable capacitors to generate a current.

Tree Metabolic Energy can be captured and used to run monitoring equipment and sensors in remote areas. Living plant metabolic energy is converted to electricity, alleviating the need for batteries. The company Voltree has demonstrated the technology and offers a variety of products.

MICROHARVESTING



MICROHARVESTING

Microharvesting is the process by which low levels of natural energy that would otherwise be dissipated or wasted is captured and converted into electrical energy. The natural energy can be in any form (e.g., solar power, mechanical vibrations, thermal energy, wind energy, salinity gradients).

The harvested micropower can be stored and/or used to power small, wireless autonomous devices, such as those used in wearable electronics, wireless sensor networks, and biomedical devices.

While energy harvesters only provide a small amount of power for low-energy electronics, the energy source is present as ambient background and is completely free!

For example, temperature gradients exist from the operation of a combustion engine. In urban areas there is a large amount of electromagnetic energy in the environment because of radio and television broadcasting. Structural monitoring equipment can be powered by the vibration energy of a bridge.

There are various technologies in use that harvest energy from blood sugar and tree sugars for conversion into electricity to power very small biological devices and monitoring equipment. Other advanced technologies include electroactive polymers, nanogenerators, and noise harvesting devices.

Output is measured in milliwatts (10^{-3} W), microwatts (10^{-6} W), and nanowatts (10^{-9} W).

Piezoelectric microharvester
Image courtesy of Ethem Erkan Aktakka, Ph.D. and the University of Michigan.

ENERGY CONSERVATION

DEMAND MANAGEMENT

ENERGY DEMAND MANAGEMENT

The cleanest and most environmentally friendly kind of electricity is the kind that is never needed nor used.

We can also help a renewable energy grid operate more smoothly if we use less electricity during peak times of the day, which is typically in the late afternoon when people come home from work and school. That happens to be the time when solar panels are starting to drop off in their energy production. That means that the utility grid needs to quickly ramp up production with peaker plants. In the past these have been natural gas-fired, but in the future the sharp spike in demand will be filled by the kinds of energy storage devices listed in the following pages. The gap between peak solar production and peak demand later in the day is sometimes called the "Duck Curve" because it resembles a duck in profile.

Peaks and valleys in demand can also be minimized with energy efficient (high performance) architecture and through the application of smart meters, time-of-day pricing, and smart appliances that know to turn on when the spot price of electricity is at its lowest. Smart grid technology allows end users to monitor in real time the power available to the grid at any point in time and plan their use patterns accordingly. Appliance control technologies can be designed to perform this function automatically.

Fully realized systems will charge consumers a price that changes in real time according to kWh spot prices as they fluctuate with demand.

Without these technologies or sufficient energy storage, renewable energy power plants sometimes must be curtailed when the grid does not have enough demand for their power. Think about this issue the next time you see wind turbines not spinning as you pass them along the highway on a windy day. This is the reason why they are stopped.

ENERGY DUCK

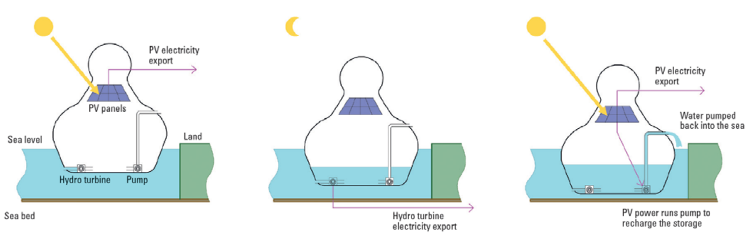
DESIGNERS
Hareth Pochee, Adam Khan, Louis Leger, Patrick Fryer

TECHNOLOGIES
photovoltaic panels (Panasonic HIT or similar), hydraulic turbines

ANNUAL CAPACITY
400 MWh

A submission to the 2014 Land Art Generator Initiative design competition for Copenhagen—LAGI 2014.

Energy Duck explains the "Duck Curve" related to renewable energy and old-fashioned power grids.



Duck Floating High
Energy storage is full.
All electricity is exported.

Duck Descending
Hydro turbine runs as storage is flooded. Stored energy is exported.

Duck Floating Low
Stored energy has been used.
PV panels power the pump. Duck rises to recharge the storage.

ENERGY STORAGE

SMART UTILITY GRID

SMART UTILITY GRID

With a large enough, well interconnected, and technologically sophisticated power grid, intermittent energy generation can be managed and matched to real time demand conditions by allowing peak electrical generation capacity in some locations to make up for lower capacity in other locations.

Thinking just about solar power for a moment, we can imagine a cloudy day in one region limiting local power generation, while the sun is shining in a clear sky 2,000 kilometers away. If those two districts are connected by a high voltage transmission line, we can make use of the peak power output of the sunny region to power the cloudy region. High Voltage DC (HVDC) is the gold standard for this kind of distant interconnection. Stranded asset gas pipelines could potentially be repurposed for gas-insulated transmission lines (GIL) in the near future, easing the burden on new corridor permitting.

Without a smart and interconnected grid, the sunny region may have had to turn off the power generation, something known as curtailment.* It's a shame to have a solar panel or wind turbine not being put to use when a distant place could use the power.

The ideal electrical infrastructure might be a system of microgrids with local and regional storage that are well interconnected with HVDC transmission lines. A central operator of an interconnected planetary electrical grid could supply power from any nation to any other.

Perhaps one day we will realize Nikola Tesla's vision of transmitting electricity wirelessly through the atmosphere providing free energy to all the world.

*Curtailment is the opposite of load shedding (a rolling blackout), where the grid operator must turn down demand by shutting off service to certain parts of the grid.

ENERGY STORAGE
THERMAL

THERMAL ENERGY STORAGE

Thermal energy storage (TES) is the storage of energy in matter that is either heated or cooled in relation to the nearby ambient environment. Thermal energy can be stored in a variety of mediums, including water, earth, stone, minerals (salt for example), metals, and air.

Some concentrated solar power plants use liquid sodium or other thermal storage mediums that hold heat for long periods and allow for the operation of steam turbines for as many as 17 hours after the sun has set. These systems have the potential to provide dispatchable power 24/7 from the sun and through most any weather condition.

Alternatively, energy can be stored by cooled liquids and ice made during off-peak hours (and when temperatures are cooler) that can then be used for air conditioning purposes in the daytime. The unit of measurement, a "ton" of cooling recalls the history of large centralized ice stores that were used to supply the iceboxes of businesses and households prior to widespread electric refrigeration.

Thermal storage media can include water or ice-slush tanks, masses of native earth or bedrock, deep aquifers between impermeable strata, earth-covered gravel pits, as well as eutectic solutions and phase-change materials.

The Drake Landing Solar Community in Alberta, Canada uses a central solar thermal heating system to satisfy 97% of the heating demand of the community.

Gemasolar plant
Image courtesy of Torresol Energy.

Young women delivering ice, 1918.
National Archives, *Records of the War Department General and Special Staffs*.

STORAGE

ENERGY STORAGE

HYDROGEN

GOYA

DESIGNER
Ruxandra Iancu-Bratosin

TECHNOLOGIES
solar photovoltaic, electrolysis, hydrogen fuel cells, microbial fuel cell

ANNUAL CAPACITY
600 MWh

A submission to the 2019 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2019.

HYDROGEN ENERGY STORAGE

Hydrogen gas can be easily produced through the electrolysis of water, a process that was first described using the word by Michael Faraday in 1834. Electrolysis requires an electrolyte substance that contains free ions. Certain types of metal, graphite, or semiconductor material meet the requirements of a suitable electrolyte. Traditionally, rare metals like platinum and iridium have been used as the electrolyte and an external source of electricity was required.

Recent advancements by researchers such as Daniel Nocera at MIT have proven the potential for inexpensive and abundant electrolyte materials that can generate their own electricity in the presence of sunlight, alleviating the need for an external power supply. Research in this area is often referred to as artificial photosynthesis, because in a plant leaf, electrolysis is the first step in the creation of sugars from carbon dioxide and water using sunlight.

Once you have a quantity of stored hydrogen, the process can be reversed using an electrochemical cell (also known as a fuel cell) that binds hydrogen with oxygen in the air to generate electricity and water.

Hydrogen fuel can also be used to generate heat, for example in a calcium hydride reactor, like the one by ADI Solar Thermal. Solar generated heat separates calcium hydride into its constituent elements, calcium and hydrogen. This heat energy can be recovered by allowing the hydrogen to recombine with the calcium in an exothermic reaction.

UNEXPECTED SCENARIOS

DESIGNERS
Riccardo Daniel, Kei Shiho, Francesco Feltrin

TECHNOLOGIES
solar thermal with Stirling heat engine, calcium hydride reactor with hydrogen energy storage

ANNUAL CAPACITY
175 MWh

A submission to the 2019 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2019.

STORAGE

ENERGY STORAGE

CHEMICAL BATTERY

land art generator field guide to renewable energy technologies (2nd Edition)

CHEMICAL BATTERY ENERGY STORAGE

Since there are differences between the time of production of some renewable energy resources and the time of consumption based on human needs, it is important to develop methods of energy storage that do not cause more harm in their production and disposal than the old forms of electrical generation that renewable energy is replacing.

There are great transitional applications for lithium-ion, nickel-metal hydride, sodium-sulphur, and other electrochemical batteries, especially as it pertains to transportation. These technologies may not be the best long term solution for utility-scale energy storage since the minerals and metals that go into their production are not always entirely renewable or easy to recycle. Research areas into less expensive and more environmentally friendly batteries include systems such as molten metal, zinc-air, vanadium redox and other types of flow batteries, and even potassium-geopolymeric composite concrete blocks that can turn buildings into batteries!

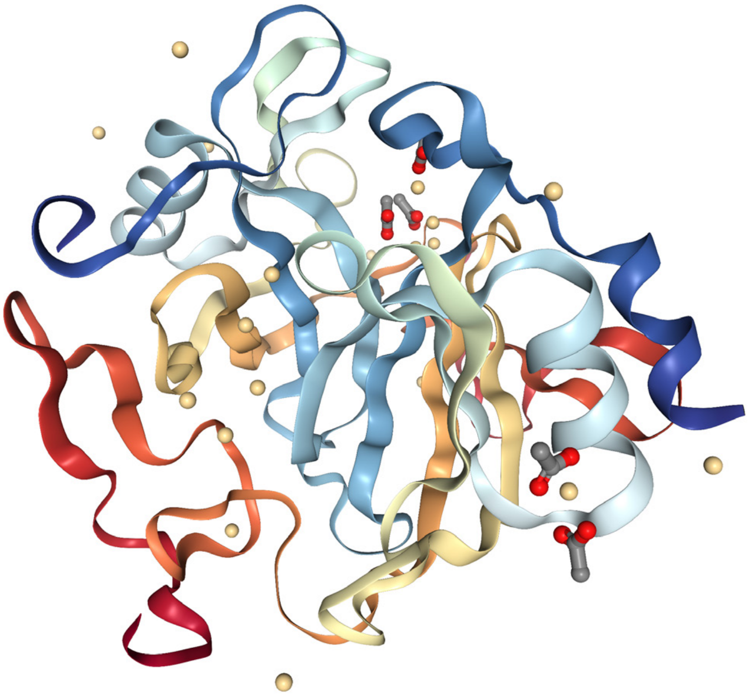
Utility-scale batteries have been dropping in price and solar+battery storage is now less expensive than natural gas peaker power plants designed to provide energy quickly to power grids to avoid brownouts. Tesla's 129 MWh (100 MW max power) lithium-ion storage in South Australia (installed in 2017) is on track to pay itself back in three years.

Energy storage solutions like these can help keep solar and wind power plants operating at their maximum capacity factor without curtailment when demand is low.

Tesla battery storage for grid stability at the Hornsdale Wind Farm, South Australia
Photo by David K. Clarke.

STORAGE

ENERGY STORAGE
GAS AND LIQUID FUEL



GAS AND LIQUID FUEL ENERGY STORAGE

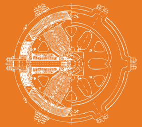
Biofuels and methane gas can be considered a type of energy storage. If renewable energy is the power used in the processing of these fuels and they are derived from renewable resources, then the energy that is embodied in them can be considered renewable.

Based on the technology, they can be helpful in reducing anthropogenic carbon emissions by delaying CO_2 pollution through multiple energy cycles, or they can be seen as net carbon neutral if derived from rapidly renewable plant-based sources that do not contribute to deforestation (like algae).

Fuels can be derived by diverting waste CO_2 streams that would otherwise be emitted directly into the atmosphere from municipal systems such as a wastewater treatment plants. This CO_2 is then stored within the fuel for a productive use. If the system that utilizes the fuel for power is also capable of re-capturing CO_2, then the overall system can theoretically be defined as net carbon neutral.

A version of renewable energy storage with methane gas is being developed by a partnership between Electrochaea and the National Renewable Energy Laboratory (NREL). Using excess clean energy from solar or wind that would otherwise be curtailed, the system splits water into hydrogen and oxygen. The hydrogen is combined with CO_2 and some other nutrients to feed a kind of bacteria that can be found in hot springs: Methanobacterium thermautotrophicus. This ancient microorganism is really good at making methane gas, which can be collected and substituted for fossil-based (hydrocarbon) natural gas.

Crystal structure of M. thermoautotrophicum
Image generated with NGL viewer (PDB ID: 1ZPS). Deposition Authors: Sivaraman, J., Myers, R.S., Boju, L., Sulea, T., Cygler, M., Davisson, V.J., Schrag, J.D., Montreal-Kingston BSGI. DOI: 10.2210/pdb1ZPS/pdb.



ENERGY STORAGE

MECHANICAL

NIGHT & DAY

DESIGNERS
Kevin Kudo-King, Annie Aldrich, James Juricevich, Evan Harlan, Vikram Sami, Erin Hamilton, Gabriela Frank, MacKenzie Cotters, Lauren Gallow, Jonathan Nelson (Olson Kundig)

TECHNOLOGIES
mono-crystalline silicon photovoltaic, pumped hydro storage

ANNUAL CAPACITY
1,000 MWh

Second Place Winner of the 2018 Land Art Generator Initiative design competition for Melbourne—LAGI 2018.

MECHANICAL ENERGY STORAGE

Compression of gas or water can be used during times of peak capacity. The pressure can then be released during times of lower production to augment power. This can be accomplished in very large quantities with the use of underground cavities.

Mechanical flywheels can be used to store energy. They consist of heavy weighted round cylinders which are designed to rotate on a central axis with as little friction as possible. Electrical energy can be put into the flywheel causing it to rotate at extremely high speeds or rotations per minute (RPM). When energy is required at a later time, the rotational energy is extracted from the flywheel, slowing down its spin.

Flywheels can provide continuous (regulated) energy output in any situation where the energy input is not continuous.

The use of the flywheel for efficient use of mechanical energy dates back to the Neolithic spindle.

Hydroelectric pumped storage uses conventional dammed hydroelectric technology to fill a reservoir with water while there is access to inexpensive electrical power. The water is then released to power turbines when electricity is required (during times of day when the cost per kWh is higher). This is a type of gravity energy storage.

Other types of gravity energy storage include weighted freight trains on steeply inclinded paths and even tower cranes that raise and lower hundreds of concrete weights arranged in orderly piles around them.

The second place winner of the 2019 Land Art Generator design competition, *Sun Flower*, is a kinetic sculpture that utilizes the potential energy of its own weight to store the energy collected by solar panels in its petals during the day. At sunset when the petals have reached their closed position they begin to fall slowly under the force of the earth's gravity, giving stored energy to the city grid.

SUN FLOWER

DESIGNERS
Ricardo Solar Lezama, Viktoriya Kovaleva, Armando Solar

TECHNOLOGIES
translucent solar photovoltaic, gravity storage

ANNUAL CAPACITY
350 MWh

Second Place Winner of the 2019 Land Art Generator Initiative design competition for Abu Dhabi—LAGI 2019.

Over the past 200 years non-renewable energy resources have helped to bring about great advancements. But their consumption has also brought great blight upon the health of the planet and her inhabitants, and our easy access to them is soon running out. But change is just around the corner...

Right now is a great time to help contribute to this change. The more we can increase public awareness and acceptance of renewable energy and local applications, the more direct our path will be to a truly sustainable world.

A FIELD GUIDE TO RENEWABLE ENERGY TECHNOLOGIES

SECOND EDITION

2nd edition (November 2019)

Authors and editors: Robert Ferry, Elizabeth Monoian
A project of the Land Art Generator Initiative

This revised edition has been produced in coordination with the LAGI 2020 Fly Ranch design challenge held in partnership with Burning Man Project.

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Back cover: *The Windmill*, Hammerstein's Paradise Gardens, New York (1900–1906). Image in the public domain. Courtesy of the Detroit Publishing Company Collection and the Library of Congress.

The future we would like to see is one in which we are surrounded by the most diverse ecosystem of renewable energy technologies and landscapes, each a reflection of local culture and context.

In this future, where you will be surrounded by beautiful renewable energy generators, you will surely need a guidebook in order to know if that thing that you find so beautiful is a semiconductor-based artificial photosynthetic cell, a piezoelectric generator, a triboelectric fabric, or a dye-sensitized solar cell.

What is the future that you would like to see? Use this book and design your own renewable energy landscapes!

—Robert Ferry and Elizabeth Monoian
Founding Co-directors, Land Art Generator

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