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ZERO ENERGY HOUSES
Geoexchange, Solar CHP, and Low Energy Building Approach

Peter Platell, PhD
LOWTE, Tilskogsvagen 15 193 40 Sigtuna, Sweden

Dennis A. Dudzik
URS Corporation Americas, Sacramento, CA 95833, USA

ABSTRACT
On March 29, 2006, the World Business Council for Sustainable Development announced in Geneva, Switzerland, that it is forming an alliance of leading global companies to determine how to design and construct buildings to use zero energy from external power grids, be carbon neutral, and be built and operated at fair market values. This paper is a contribution to the many possible Zero Energy House (ZEH) solutions that deserve further attention. The geoexchange, solar thermal combined heat and power (CHP), and low exergy building approach to ZEH is based on select R&D projects that, together, imply several important synergies. Not using "overqualified" energy in the house (i.e., energy quality, or exergy) is a significant step toward realizing a cost-effective ZEH. Most of the energy conversion and energy storage can be obtained through the appropriate use of purely renewable solar energy. However, a fuel reserve is needed to assure all of the building's energy needs are met 24 hours a day, 365 days a year. The future ZEH implies the production of this fuel, potentially as hydrogen or alcohol, by using CO_2 plus water synthesis, powered by solar heat from concentrating solar power (CSP).

INTRODUCTION
In 2001, the construction market represented 20% of the U.S. economy, comprising 12.7% of the $10 trillion U.S. Gross Domestic Product (GDP). According to the U.S. Department of Energy (DOE), buildings represent 39% of the country's primary energy use, including fuel input for production. The EPA estimates that 136 million tons of building-related construction and demolition debris are generated in a single year. Once erected, buildings represent 70% of the U.S. electricity consumption. Furthermore, buildings today are almost exclusively dependent on energy supplied from outside, even though they have significant potential for self-support using renewable energy. Buildings have the physical potential to harness diluted and sometimes unpredictable renewable energy. The building envelope and the ground constitute the basic resources for energy autonomous buildings.

A building needs different types of energy quality, or exergy, as it is called in thermodynamics. For instance, high quality energy, as electricity, is needed to run water pumps, fans, and computers. Low temperature heat energy is needed to provide a comfortable indoor climate and for refrigerators and freezers; heat energy at a higher temperature is needed to warm water.

All of these different energy qualities are created in an environment of approximately 0°C to 25ºC in most of the world. Some countries have a marked inland climate, where temperatures vary substantially from summer to winter. These countries need more energy to provide a comfortable indoor climate.

NOMENCLATURE
<u>Ground-Coupled Heat Pumps.</u> By upgrading the home heat pump's temperature source from the air to the ground, about three times more heat energy can be supplied to heat space than the energy used to propel the heat pump. In addition, with several appropriately designed and configured ground heat exchangers (the ground loop), it is possible to employ the ground sensibly to store heat.

<u>Low Exergy Buildings.</u> Heat pump efficiency can be increased by adopting so-called low exergy cooling and heating of buildings (www.lowex.net). (See ASHRAE's technical group, TG1 Exergy Analysis for Sustainable Buildings [contact mvaughn@ashrae.org].) A low exergy approach means that the supplied energy quality (temperature) is close to the desired temperature (the room temperature for heating and just a few degrees below room temperature for cooling).

The LOWTE ZEH. Besides the low temperature energy need, there is a need for high quality (high exergy) energy as electricity for electric motors, computers and lighting. The LOWTE ZEH, also known as an Energy Autonomous Building (EAB), generates its own electricity using CHP. Modern, high performance small-scale solar thermal steam engine systems offer all of the desired qualities that local CHP demands. An innovative steam buffer provides short-term energy storage.

GEOEXCHANGE

The average temperature in the ground is relatively close to the desired indoor temperature (+20ºC) in all of the populated areas of the world. By upgrading the temperature source from the ground to the HVAC system temperature with a heat pump, about three times more heat energy can be supplied to heat space than is used to propel the heat pump. However, when the electricity is generated with an average efficiency of about 30% in the large centralized power plant, it is not sufficiently energy efficient.

A new design for ground heat exchangers (the ground loop) [1] is illustrated on Figure 1. It is possible to exploit the ground more efficiently with this TIL-pipe design. Figure 1 illustrates a typical vertical temperature gradient.

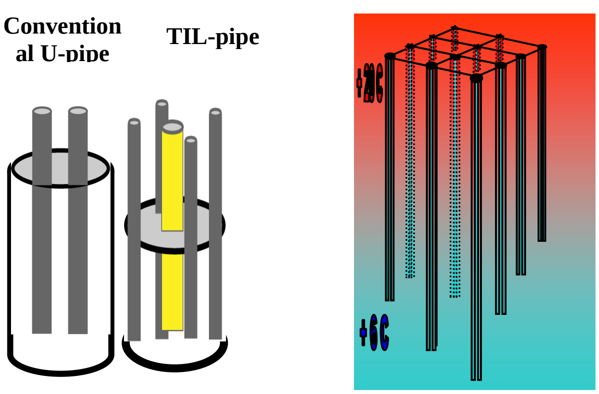

Figure 1. Ground Energy Storage, in the Ground, with Vertical Temperature Gradient

Compared to conventional ground couple heat pumps, this form of ground energy storage provides several advantages [2]:

- Higher performance per meter (W/m);
- Lower heat losses;
- Lower supply temperature during summer seasons;
- Lower pressure drops; and
- Small footprint.

With the ground heat exchangers using TIL-pipe, it is possible to create energy storage rather than considering the ground as a heat source or heat sink. The Coefficient of Performance (COP) can be increased by a factor of two or more with appropriately designed energy storage [2]. The cool end supplies cooling during summer, and the warm end supplies heat to the heat pump during winter.

LOW EXERGY BUILDINGS FOR SPACE CONDITIONING

Heat pump efficiency can be further increased by adopting low exergy cooling and heating of the buildings (www.lowex.net). With the low exergy approach, the supplied energy quality (temperature) is very close to the desired temperature (room temperature). During winter, a supply temperature only a few degrees above the desired room temperature is needed. In a double-slot low exergy building (illustrated in Figure 2), the outer slot return temperature is considerably below room temperature. During winter, the “cool” is harvested and fed into the water ground loop. During summer, the supply temperature is only a few degrees below the desired room temperature, and the return temperature is considerably higher than room temperature. That is, the building envelope acts as a cooling panel while also acting as a low-temperature solar collector.

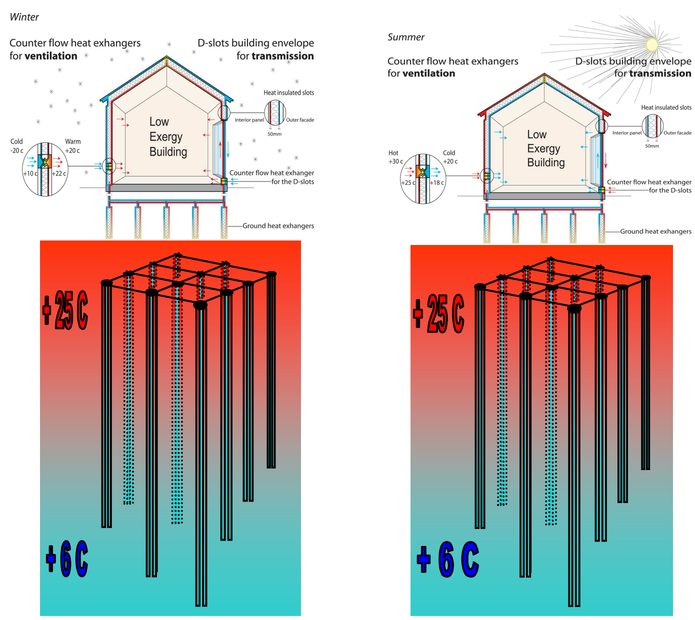

Figure 2. ZEH Winter Time and Summer Time

Figure 2 illustrates a house in which the low exergy approach has been emphasized. This low exergy building needs only a small amount of high exergy energy for pumps to circulate the water in the ground heat exchangers and for fans for the double slot-building envelope. A significant temperature difference between the supply and return flow means low pump power consumption. There is hardly any need for additional energy to maintain a comfortable indoor climate, which includes dehumidification in most of the world.

With low exergy buildings, as illustrated on Figure 1, it is possible to exchange surplus heat (solar energy) in the building to ground (space cooling) and from the ground (space heating). Almost no energy is needed, other than for pumps and fans. The pumps and fans in the ground loop and in the building (HVAC) operate with high ΔT between supply temperature and return temperature [3] and hence with low mass flow and low pressure drop.

HOT WATER, REFRIGERATORS, AND ELECTRICITY

Besides energy for space conditioning, higher temperatures are needed to warm water. With the ground energy storage shown on Figure 1, the heat sources (15 to 25°C) in the ground will mean high COP for a heat pump producing warm water. Lower temperatures for refrigeration and deep freezing could be obtained with a high COP because there is a heat sink with low temperatures in the ground; hence, only low temperature lift is needed for cooling processes.

In addition to the low temperature energy needs cited, high quality energy (exergy) as electricity is needed for electric motors, computers, and bulbs.

The ZEH energy autonomous building generates its own electricity when CHP is employed. Several important issues have to be addressed to achieve attractive local on-site CHP. The CHP has to be able to provide electricity and heat independently because the needs for electricity and heat do not always coincide. Furthermore, the CHP must have the very best efficiency at part load, rather than at full load. With a local CHP, the average power need is very small, compared to the potential required peak power. Peak power requirements are about 10 times higher than average power requirements.

Today, micro gas turbines, and the internal combustion engine (ICE), are the most common types of technology for implementing small-scale, local, on-site power. As a future power source, the fuel cell is highlighted. However, modern high performance, small-scale steam engine systems seem the best option for obtaining all of the desired qualities that local CHP demands.

First, external combustion at a fairly low temperature allows for the possibility of using any local fuel. A steam engine could be adapted, with different types of burners, for local, available, primary energy resources as bio-fuel.

Furthermore, a steam engine system can use solar energy when it is available. Today, only large-scale solar thermal power exists. But this technology could be downsized by integrating a concentrator (parabolic trough) into the building envelope. When the sun is failing, the steam engine is powered with locally available fuel. In summer, when space heating is not needed but there is still a need for electricity generation, the ground will act as a heat sink, storing surplus heat until winter. This allows for good matching between electricity and heat requirements during the whole year, and it entails a low capital cost.

SOLAR-POWERED CO_2 RANKINE-CYCLE

Solar energy can be harvested in several ways. When it comes to generating electricity, the most well-know technology is photovoltaic (PV). Another approach is solar thermal power involving the evaporation of water that is expanding, for example, in a turbine. Other working fluids such as organic Rankine cycle (ORC) also can be employed because they can make use of a lower temperature, which in turn involves simpler and cheaper solar collectors. These non-environmentally friendly working media are unfavourable.

Compared with the traditionally used working fluids in ORC, CO_2 is an environmentally friendly natural working fluid that offers many advantages. It has no ozone-depleting potential (ODP) and negligible global warming potential (GWP=1). Furthermore, it is inexpensive, non-explosive, non-flammable, and abundant in nature. Given its low critical temperature (7.38 MPa, 31.1 °C), a CO_2 power cycle works as a transcritical cycle. This means that the heat is transferred to the working fluid in a supercritical region, which avoids the two-phase flow instability that occurs in the absorption tubes when direct steam generation is used. If water is going to operate with supercritical pressure, a pressure above 22 MPA has to be used, which cause stress challenges.

Comprehensive studies of transcritical CO_2 power cycles have been performed [4,5]. Given the advantages of CO_2, it has been selected for the ZEH. Figure 3 illustrates the transcritical CO_2 power cycle on a temperature and entropy graph.

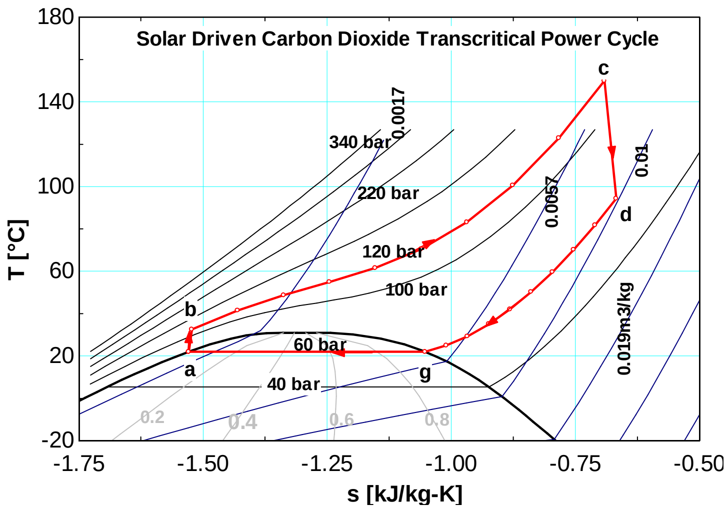

Figure 3. Transcritical CO_2 Power Cycle

HIGH-TEMPERATURE ENERGY STORAGE

The new type of ground energy storage illustrated in Figure 1 offers an inexpensive way to store low-grade heat for space-conditioning. However, to obtain needed high quality energy storage [6,7], favourable characteristics are required in regard to the following:

- Energy quality;
- Degradation of energy quality during the discharge process;
- Degradation of energy quality during the storage process;
- Energy density (kWh/kg and per volume);
- Power density (kWh/kg and per volume);
- Life cycle (low degradation due to cycling); and
- Calendar life (low degradation due to aging).

In general, electric batteries have several drawbacks relative to these qualities.

When the ZEH is using a Rankine cycle for CHP, a thermal energy storage "steam buffer" is proposed for short-term, high-temperature, energy storage [8]. The steam buffer offers high temperature heat storage through the use of a porous ceramic, metal foam, or micro channel material. The steam buffer is charged by feeding CO_2 steam through it; the heat is dissipated into the storage material, where it is stored as sensible heat. The very small amounts of high temperature and pressurized steam in the steam buffer imply no hazard, even if a breakdown should occur. (This system should not be associated with the old, so-called steam accumulator, which was dangerous when something went wrong.)

The steam buffer is a generative heat exchanger that offers the high utilization of the material (i.e., the steam buffer is an efficient regenerative heat exchanger with high energy density and a very high power density). When it is sensible heat that is stored, the energy density depends on the stored temperature. At 600°C the heat energy density is approximately 150 Wh/kg heat.

When the energy density is not critical, impressing the power density is more attractive. Computer simulations indicate that power density can be as high as 10 kW/kg, or even higher. That means a high capability to absorb intermittent renewable energy and to offer prompt provision of power, when needed.

MEU–MULTI ENERGY UNIT

The ZEH concept described involves heat pump mechanical refrigeration and a combined heat and power unit. All of these functions are implemented using the same components: high-pressure counter-flow heat exchangers and compressors/ expanders.

Figure 4 shows two units that are implemented by components that are virtually the same. One unit is operating as a power cycle; it provides shaft power to the other unit, which can provide cooling and hot water temperatures. If the sun is shining, the CSP collector, a parabolic trough, is heating the supercritical CO_2 to about +200°C. CSP that operates with a higher temperature is possible, but one of the advantages with CO_2 is its ability to offer attractive efficiency if a low temperature heat sink is available. Figure 5 shows the efficiency of a CO_2-Rankine cycle at different pressures and temperatures. The condenser temperature is set at 22°C. The ground will act as an effective heat sink, and the heat that is fed into the ground is stored, with low heat losses, until winter. If space heating is needed, the low-grade heat rejected in the condenser also can be used directly in the double slot.

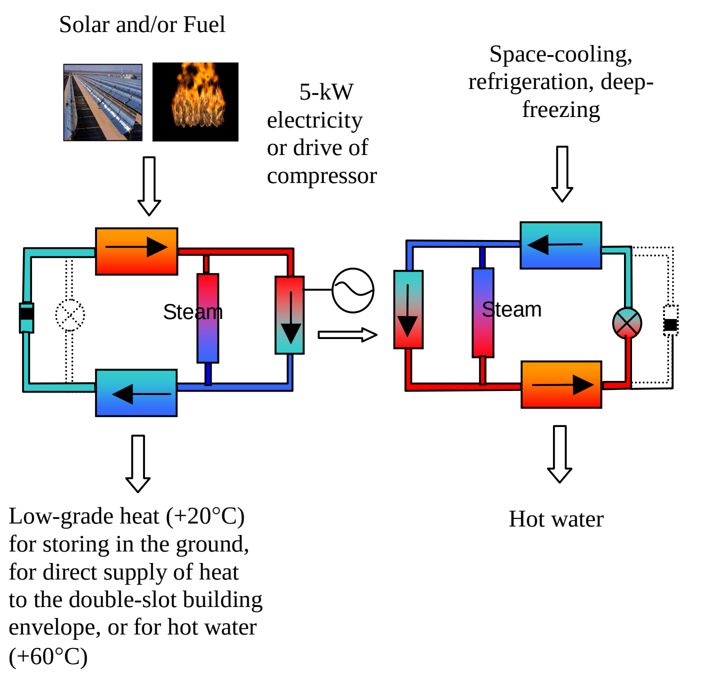

Figure 4. MEU–Multi Energy Units

As shown on Figure 5, the efficiency is about the same as a PV (15%) at 200°C admission temperature to the expander. However, these efficiency numbers are valid for a CO_2 Rankine cycle system, where the steam exhaust temperature after the expansion (about +60°C) is used for hot water. If an external heat exchanger that makes use of the exhaust steam is integrated to preheat the supercritical CO_2 (a regenerative cycle),

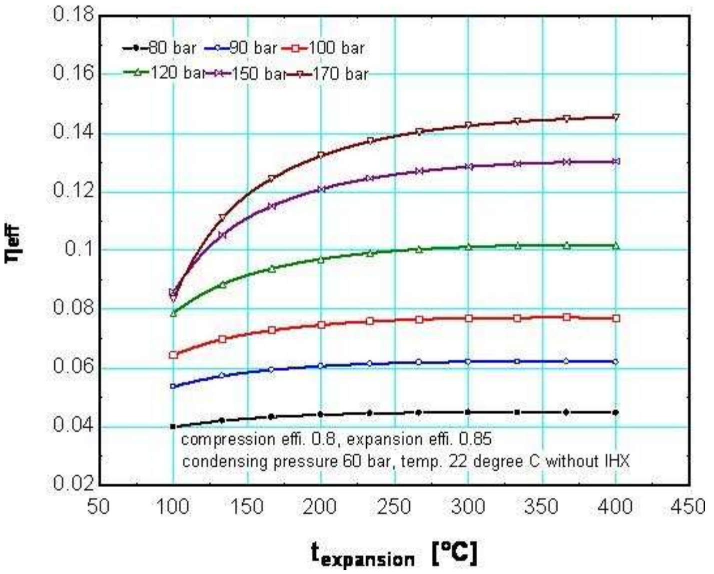

Figure 5. Efficiency (Electric) Without Internal Heat Exchanger

efficiency can be considerably higher. Figure 6 illustrates the efficiency (electric) for the CO_2 Rankine cycle system equipped with external heat exchangers with counter-flow characteristics. The efficiency is slightly higher at a low-admission temperature, but at a higher temperature the efficiency is considerably higher with an internal heat exchanger. Hence, an effective regenerative power cycle is implemented. When a fuel is burned, it is typical to obtain a 400°C to 500°C admission temperature; thus, an efficiency of 25% is possible. This is on the same order of magnitude as most other micro power technologies.

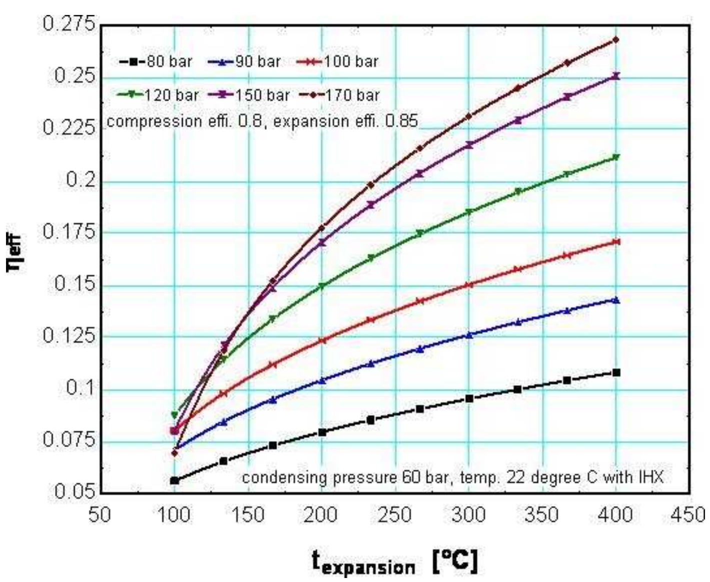

Figure 6. Efficiency (Electric) with Internal Heat Exchanger

CONCLUSION

By being exergy aware, it is possible to reduce total building electricity demands and to match various temperature profiles to obtain significant overall energy efficiency improvements.

The described ZEH concept is based on different R&D projects carried out over several years and brought together to form a cost-effective ZEH. Some stumbling blocks will have to be overcome before a commercial product is available. Most crucial is the implementation of an oil-free, CO_2 Rankine cycle expander/compressor. In addition, the valve and control technology must be further developed.

Supercritical CO_2 acts as a strong detergent and will wash away oil and similar lubricants. Oil, as a lubricant, is not a good choice when the unit is operating as an expander fueled by combustion gases at a high temperature. Oil degradation is a factor at possible combustion temperatures of 450°C.

The ZEH employing the CO_2 Rankine cycle is expected to offer attractive cost benefits. Similar mass-produced automotive air conditioning units are likely to emerge in that market in the near future. It is too early to draw final conclusions about the total system economics, but when several of the new component costs offset the cost of conventional components, there is a potential to offer an attractive payback period to the end user.

ACKNOWLEDGMENTS

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