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Right-sized Geothermal Tetrageneration™ for Eco-tourism Clusters and Better Lives for Host Communities in the Developing World

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ABSTRACT

The first of two perennial challenges for efficient cost-effective combined heat and power (CHP) schemes has been the assurance of steady customers throughout the day for both the electricity and heat outputs in order to balance flows and minimize the need for, and capital expense of, thermal energy storage. The other challenge has been to co-locate these consumers in order to minimize the extent of the heating district, hence the capital expense of the transport infrastructure, especially the steam or hot water pipelines. In addition, for geothermal CHP, steady flow is often a necessity on the supply side in order to avoid shutting in production wells, which imposes yet another requirement for either steady flow on the demand side, or expensive storage. Cascading direct users from high-grade to low-grade heat only compounds this problem of synchronization and marshalling, although geoexchange tricks such as asynchronous aquifer thermal energy storage could be useful. Most CHP and direct-use developers focus on factories as users of heat, but factories do not operate around the clock. Because their thermal demands are episodic not steady, many promising candidates for direct-use are rejected at the first stage of economic analysis. We suggest that developers should expand their horizons instead.

Herein, the authors present their geothermal Tetrageneration™ concept, right-sized for an eco-tourism/hospitality/health care cluster built around the well(s), which would provide sustainable employment, electricity, sanitation and a better life for the host community. Eco-tourism is one of the developing world's most sustainable, low-impact but high-value, rewarding, and promising sectors for economic development in the 21st century. Most of the countries on the Ring of Fire possess these two: unique ecological areas and geothermal resources. The final piece of the puzzle is that geothermal resources of the east African Rift system (EARS) tend to be near or within the world's most famous wildlife parks.

Eco-tourists do expect a certain standard of sanitation and accommodation, which means lots of clean hot water, almost around the clock, for bathing, cooking and doing laundry. However, there is another user generally overlooked by developers: community health and sanitation. Community clinics also need lots of clean hot water, almost around the clock, for sterilizing, bathing, cooking and laundry. A convenient mnemonic for this pairing might be "hospitality and hospitals". With proper design, each thermodynamic use can be efficiently cascaded, from higher-order forms such as live steam and electricity, to lower-order uses down the chain of benefit, before the primary geofluid is injected back into the reservoir, thus assuring its long-term health too. It goes without saying that modularizing such a system to fit into standard twenty-foot-equivalent-unit (TEU) form factor makes it transportable anywhere on earth, and extensible as well. One of the authors conceived one such quadruple system for Tetra Tech that is called Tetrageneration™.

1. INTRODUCTION

In engineering, the word "***generation***" is reserved for the development of ***useful energy*** (either mechanical ***work*** or ***electricity***) by ***engines*** (hence the name of the field) from some source of ***primary energy*** in nature. (***Motors***, on the other hand, simply transform one form of already-converted stored energy to another.) In all real cycles, the majority of the primary energy is lost as waste heat due to the fundamental laws of nature, specifically the Second Law of Thermodynamics. Thus:

cogeneration is the generation of <u>two</u> useful effects from the same input of primary energy—the usual example being generation of electricity as a by-product of heat from a furnace. (Note that when two different cycles are used to generate electricity, for example the air-mediated Brayton Cycle followed by the water-mediated Rankine Cycle as is done with most natural-gas-fired power plants today, it is correctly called ***combined cycle***, not cogeneration.) Hence

trigeneration is the generation of <u>three</u> useful effects from the same input of primary energy—one example being:

1. motive power or electricity generation (first effect)
2. followed by direct use of the waste steam for industrial process heat, desalination, hot water or space heating or any|all of these in parallel (second effect),
3. followed by chilling water for air-conditioning via any one of a number of low-pressure-steam-fired absorption-chilling cycles such as water-ammonia or lithium-bromide.

A decade ago, one of the authors (Kennedy) added another term in logical succession to the lexicon of engineering:

tetrageneration™, the generation of <u>four</u> useful energy effects thermodynamic cascades from the same input of primary energy. See Figure 1. The same three effects described above can be followed by the fourth: for example,

4. dehumidification via recharging desiccants using the now very-low-grade steam or thermal waste that is normally released to atmosphere. In humid climates, condensing unwanted moisture from interior air, i.e. removing latent vs. sensible heat, can make up to 30% of the work an HVAC system must do, which is a substantial fraction of the load.

Other chains are also possible, and can be multiplexed in almost any order. (The correct generalized term for all of these higher-order methods taken together is ***polygeneration***.)

2. TETRAGENERATION™

It was mere luck that the first part of the new term both included the name of the inventor's employer, while also carrying on the tradition of using Greek prefixes, hence "tetrageneration" not Latin i.e., "quadgeneration".

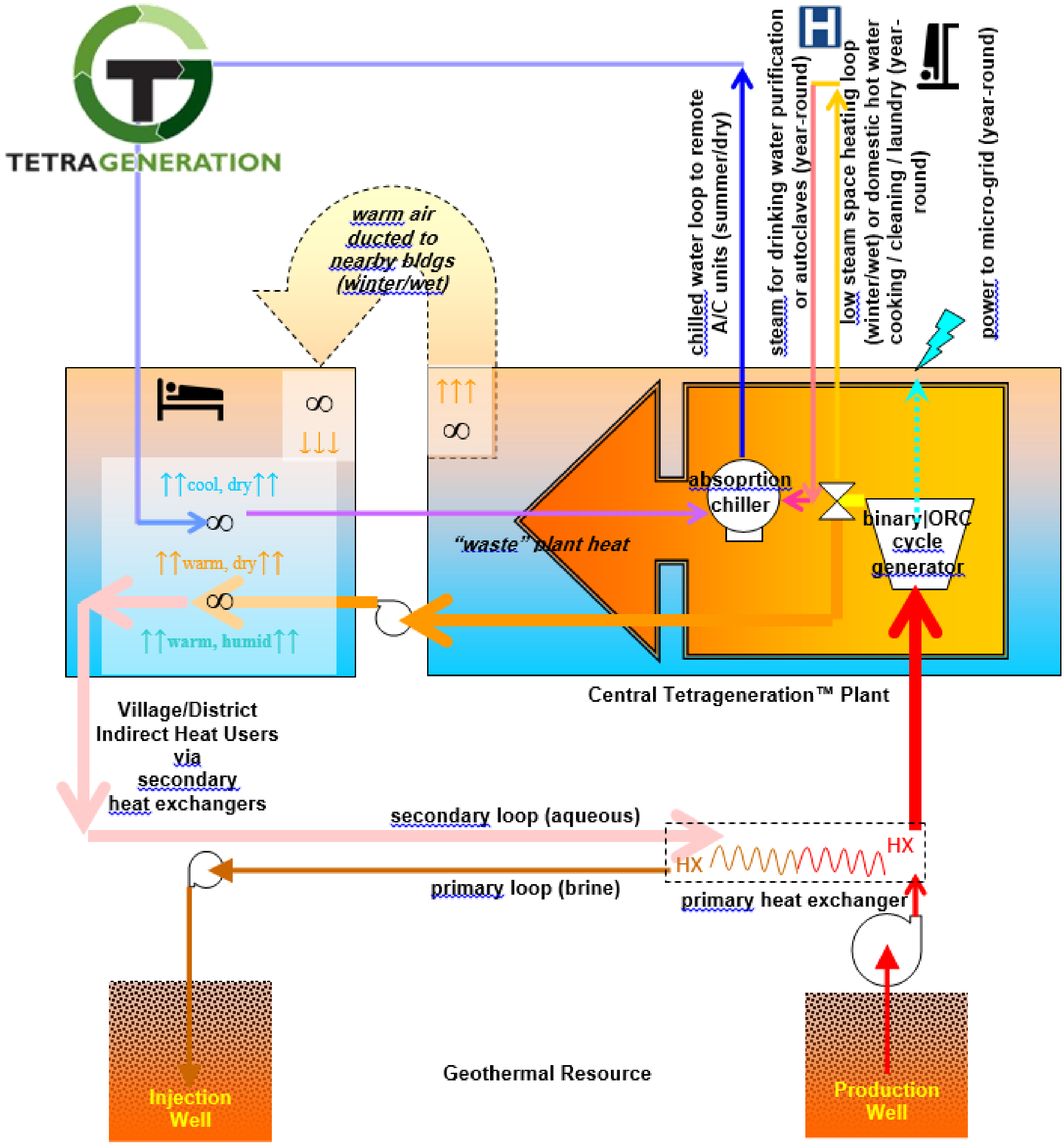


Figure 1: Conceptual schematic of a Tetrageneration™ community centered on a small geothermal resource.

2.1 Climate Change and the Carbon-Water-Energy Nexus

The steady-state primary power demand of the human race, from all sources, is about 20 trillion thermal watts, which is of the same close order as the flux of geothermal energy up through the surface of the entire earth, land and sea. Presently, about three-quarters of the energy applied by the human race is in the form of heat at the point of end-use; less than one-quarter is electricity, although this fraction is increasing. Electricity is expected to comprise half of all energy end-use by mid-century (DNV-GL, 2018).

Presently, about three-quarters of the primary energy consumption of the human race comes from fossil fuels, although this fraction is decreasing. About half the world's energy use is forecast to be carbon-free by mid-century (DNV-GL, 2018). These trends are driven by the accelerating installation of solar and wind power as well as the accelerating adoption of electric vehicles. Nevertheless, there is no cause for complacency—even in a completely carbon-constrained future, the world is going to miss the agreed-upon in the Paris Agreement by several degrees C.

The environmental cost is incurred at extraction and initial conversion when greenhouse gases (GHG) are released. The most powerful GHG is in fact H_2O. Because our planet is a water world, 90% of the harmful effects do not have to do with temperature *per se*, but water: too much or too little when and where it's supposed to be, more frequent extreme weather, and disruptions to agriculture and food supply. Furthermore, in the developed world, power generation from conventional thermal methods has a water footprint just by itself greater than all farming in the developed world. For these reasons, scientists and policymakers refer to the "carbon-water-energy nexus". In the developing world, the demand for electricity is acute, because electricity is the critical ingredient for a better life. However, the need for basic thermal energy for simple domestic tasks like cooking and washing must not be ignored, because it is this demand for fuel that is driving deforestation, causing a whole other set of problems.

It should also be noted that polygeneration is not limited to electric power, for "*electricity is civilization, but* [clean] *water is life*". Safe water is an absolute necessity for modern life—the march to modernity, medicine and the modern lifespan began with simple public sanitation, not electric power or wonder drugs. It is true that desalination as currently practiced (primarily reverse osmosis, RO) is extremely energy-intense. Worse, that input for RO plants must be in the form of electricity, because the materials problem inherent in desalination with thermal methods (e.g., multi-effect distillation of seawater) have not been mastered yet. For example, when sodium and chloride ions are removed from a solution, it totally loses its buffering capacity, at which point small changes in chemistry cause large swings in pH. Then, under the high temperature conditions inside a thermal desalination flask, it is possible for the "flux reaction" to actually run in reverse. In this harsh regime, even stainless-steel machinery will quickly eat itself. The ferocious corrosion of hot saltwater, i.e., brines, is a familiar problem to the geothermal industry. However, lower grades of heat, such as that rejected by power plants, are sufficient to disinfect water enough to make it suitable for domestic non-potable uses.

2.2 Thermodynamic Cascades

Why not put the heat rejected during electricity generation to use? If the waste heat could be utilized, it would displace heat that would otherwise have to be produced by burning yet more primary fuel. Even though polygeneration tends to require more capital equipment, polygeneration provides its benefits for zero cost in fuel, which makes it much more sustainable over the long term.

Figure 2 presents a panoply of applications for geothermal heat as a function of temperature. At the right end, power generation from "high temperature" (>200°C) sources—steam, natural hydrothermal geofluids or artificial aka "engineered geothermal systems" (EGS). Lesser quality (>150°C) sources can be exploited with binary cycles, in which the moderate temperature water is passed through a heat exchanger, where it heats a second liquid—such as isobutane or other organic liquid—in a completely separate closed loop. The liquid boils at a lower temperature than water, so it is more easily converted into vapor to run the turbine. New "organic Rankine cycle" (ORC) and Kalina cycles allow the useful extraction of electricity from even weaker "very low temperature" (<100°C) resources. "Direct use" typically involves waters under 50°C for industrial process heating or to directly heat interior spaces, swimming pools, or entire communities (district heating). See Figure 3. One application can follow another, using ever-lower grades of heat in a beneficial chain, almost down to room temperature, before the primary geofluid is injected back into the reservoir thus maintaining its long-term health too. Water is the miracle fluid, ideal for transfer of geothermal energy. Water's extraordinarily high heat capacity, four times as great as most other materials, makes it capable of carrying more heat per unit volume than any other common fluid. (This property in fact is what keeps blue Earth habitable, else we would be a snowball.)

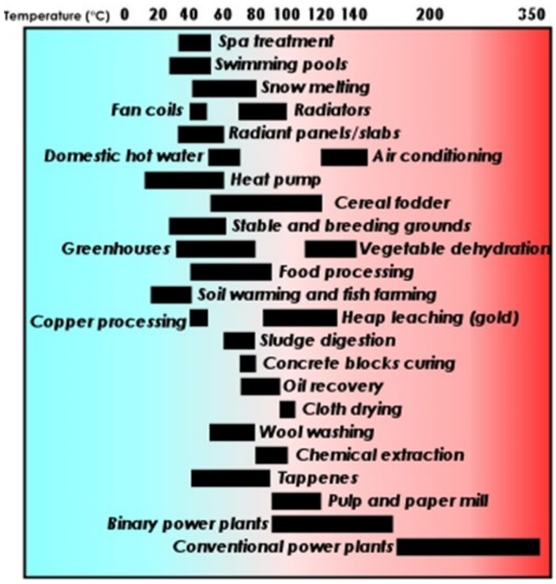


Figure 2: Applications for heat across the spectrum of temperature.

2.3 Heating Districts

A heating district is a good way to utilize very-low-grade heat that would otherwise be rejected to the environment and wasted. This application is almost as old as civilization itself.

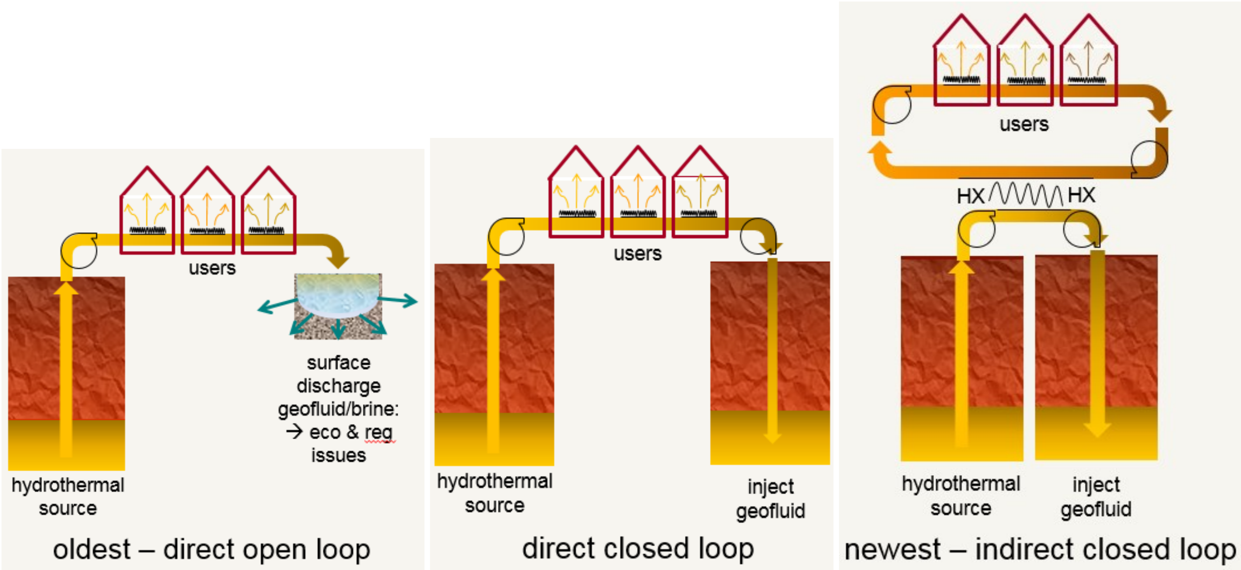


Figure 3a-3c: District heating configurations – from old (L) to new (R)

International best practice now frowns upon running open cycle (depicted on the left in Figure 3a). In many jurisdictions, the direct discharge of spent brine (which often contain heavy metals and noxious gasses) to the environment is forbidden. Open discharge also unnecessarily depletes the hydrothermal resource.

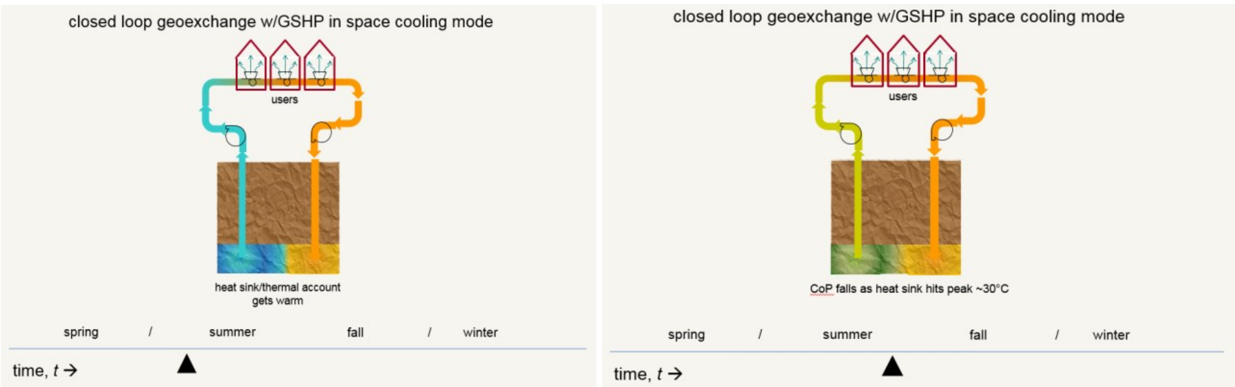
However, closing the loop (middle Figure 3b) can still be problematic in that many brines are highly corrosive. It would be better if no hardware were exposed to brine, especially the expensive rotating machinery.

Modern district heating loops employ a secondary loop of benign working fluid (on the right in Figure 3c), such as propylene glycol-water solution, on the user side of the heat exchanger. This allows much cheaper HDPE to be used in secondary mainlines vs. costlier steel without loss of durability. Harsh corrosive brine is immediately returned to the aquifer for reservoir maintenance.

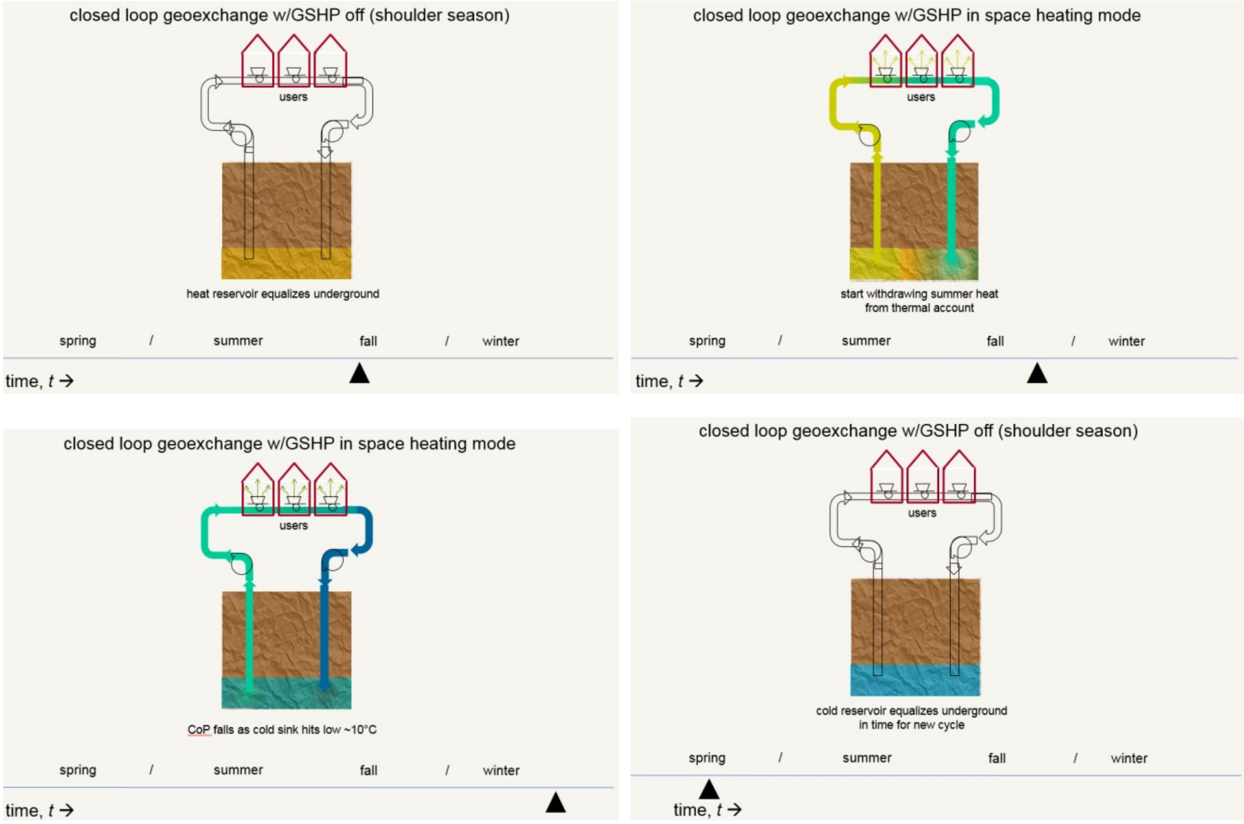
2.4 Geoexchange

2.4.1 Synchronous geoexchange

Geoexchange is the use of subterranean mass and temperature differentials with respect to ambient surface conditions as a "thermal bank account". ***Ground source heat pumps*** (GSHP) are often called "geothermal heat pumps" but this is a misnomer. Unlike true geothermal power generation from deep magmatic flows that are driven by radiogenic heat and the primordial energy of Earth's accretion, geoexchange does not extract heat from nature nor does it produce heat by combustion. Geoexchange is simply moving heat around, into and out of the ground, generally at shallow depths. It can be thought of deposits into and withdrawals out of underground thermal account, plus some transaction cost either way, due to pump work and/or inherent entropy in vapor compression cycles. As with monetary bank accounts, the deposits and withdrawals out of a thermal account must remain in approximate balance over the course of a full year or the system will eventually fail to work. Ideally, the integration (area under curve, or degree-days) of seasonal heating is approximately balanced (near-equal areas) by seasonal cooling. Figures 4a-4f illustrate this sequence (the black triangular pointer shows the time of year):



Figures 4a-4b: Geoexchange operation over a year, beginning at early summer (L) continuing to late summer (R)



Figures 4c-4f: Geoexchange operation continued, from off in autumn (UL) through winter (UR, LL), then spring (LR)

2.4.1 Asynchronous geoexchange

When storage is added to the picture, temperature differences can be exploited across space as well as time, even seasonally. Although a full treatment of geoexchange is beyond the scope of this paper, we hereby note that it is possible to purposely create both cooling and heating reservoirs, beyond those obtainable with GSHP, both on and under the ground. For example, in the right climate, a surface reservoir of discharged working fluid, exhausted of heat, can allowed to fully ice over for later application to space cooling and subsequent reinjection to the cold reservoir, displaced in time by two seasons. This is known as asynchronous aquifer thermal energy storage (ATES).

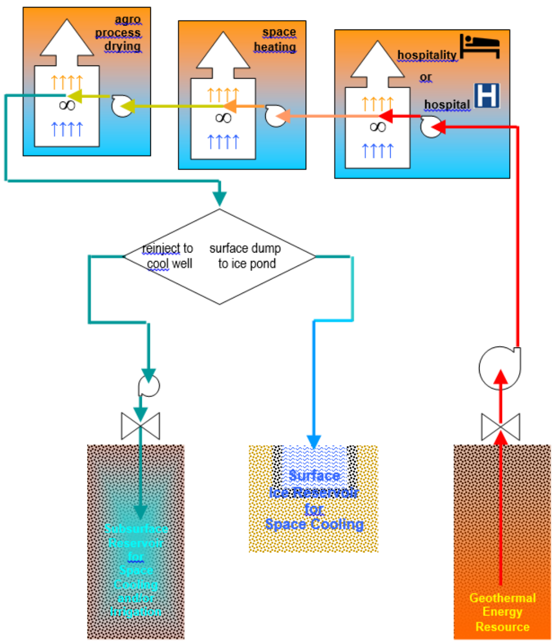


Figure 5: Conceptual direct use cascade in a four-season climate using ATES.

2.5 Correlation of Geothermal Resources and Sites for Eco-tourism

It is a peculiar gift of nature to our industry that many of the most spectacular and beautiful places on Earth also happen to be the best geothermal areas—anywhere on the Ring of Fire, for example. Eco-tourism is one of the developing world's most sustainable, rewarding, and promising sectors for economic development in the 21st century. This is turn imparts a better appreciation by visitors of what the natural world provides. Except for transportation, eco-tourism has a much lower physical signature, when done right, than smokestack industries. It is low-impact yet high-revenue. Eco-tourism is service- and education-oriented, making it align with advanced socioeconomic development. Eco-tourism must have the buy-in of indigenous stakeholders or it will not work; the authors have personally observed that successful eco-tourism enterprises involve, and benefit, the entire host community, with a variety of occupations. On the other hand, eco-tourists expect a certain minimum of hospitality, else they will not come. However, providing access for eco-tourists without degrading the very same places they traveled so far to witness is a constant conundrum. Nevertheless, the authors have personally witnessed that perfectly acceptable accommodation and amenities can be provided for an order of magnitude less power (<<1 kilowatt per capita) than ordinary life in the developed world (>10 kW per capita).

Protected areas in east Africa (outlined in dark green in Figure 6 below) are directly crossed by the EARS itself (the Eastern Arm denoted by wide red dashes, the Western or "Albertine" Arm by narrow orange dashes) and contain obvious geothermal manifestations. Particularly notable ones familiar or known to the authors include (the list is far from complete):

(Ethiopia): Abijatta-Shalla N.P., Awash N.P.,

(Rwanda): Volcans N.P.,

(Tanzania): Ngorongoro Conservation Area, Ngozi Crater. (Mnjokova, et al, 2015),

(Uganda): Bwindi Impenetrable N.P., Mgahinga Gorilla N.P., Queen Elizabeth N.P., Rwenzori Mountains N.P.

Figure 6: Protected Areas of East Africa in Relation to the EARS, Eastern and Western Arms.

2.6 The Value Proposition

The twin Achilles heel of CHP schemes has always been a problem of space coupled with a problem of time. To wit, (a) the assurance of steady customers throughout the day for both the electricity and heat outputs in order to minimize the need for, and capital expense of, thermal energy storage, and (b) co-locating these consumers in order to minimize the extent hence capital expense of the transport infrastructure, especially the steam or hot water pipelines. In the developed world, such infrastructure can run >$100K per km per megawatt-thermal (MW_t). For geothermal CHP, steady flow is often a necessity on the supply side in order to avoid "shutting in" production wells, which in turn imposes a requirement for either steady flow on the demand side, or expensive inefficient thermal storage. Cascading direct users from high-grade to low-grade heat only compounds this synchronization challenge, although geoexchange tricks on the temporal axis such as asynchronous aquifer thermal energy storage could be useful in the future. Most CHP and direct-use developers focus on factories or aqua-/agricultural processors as users of heat, but factories generally do not operate continuously, especially in the developing world. Because thermal demands from such facilities are episodic not steady, many potentially promising direct-use options are rejected out of hand. This is a mistake. Fortunately, there are two major market sectors where demand for electricity and demand for heat are always high, and always near to each other: "hospitality and hospitals" (a convenient mnemonic).

Eco-tourists expect a certain standard of sanitation and accommodation, which means lots of clean hot water, almost around the clock, for bathing, cooking and doing laundry. Community clinics also need lots of clean hot water, almost around the clock, for sterilizing, bathing, cooking and laundry.

Waterborne disease kills millions of people per year in the developing world. In addition, a great deal of time is absorbed by extremely low-value-added drudgery such as fetching water or gathering fuel wood for cooking, mostly by women. Current economic analysis that focuses only on industrial direct use such drying crops, or limiting the potential market to what a Western tourist would pay for a hot tub, completely overlooks the enormous value of providing clean safe water to people as well as ample domestic hot water (albeit non-potable) for common tasks such as cooking, cleaning, washing, or the opportunity cost of not doing so. This oversight should be rectified.

We now have all the pieces geothermally-fired Tetrageneration™ concept, right-sized for an eco-tourism/hospitality/health care cluster built around the well(s), which provides electricity, heat, sanitation, sustainable employment opportunities, and a better life for the host community. Geothermal power is well suited to this situation because it has a small footprint hence compatible with other land uses. It is clean, quiet, low-emission, reliable, and provides long-term cost savings compared to fossil fuels, especially imported oil. Admittedly, it is more complicated than a simple diesel-fired generator, and it is highly restricted to locations with an appropriate geothermal resource, but these locations have already been seen to be correlated.

"Right-sized" in this context not only means a water-energy system that is complete but no bigger than the community (or surrounding natural area that tourists are paying to see) needs, it also means one that is readily moved and set up. Based on the authors' experience in east Africa, a host community may contain several hundred souls, therefore "right-sized" means a system on the order of 100 kilowatts-electric (kW_e) at most, and no more than 1 MW_t. It goes without saying that modularizing and skid-mounting such a system to fit into standard twenty-foot-equivalent-unit (TEU) form factor makes it transportable anywhere on earth, and thus makes this model of sustainable development extensible as well to wherever a Conex box can reach.

3. CONCLUSION

Eco-tourism is one of the developing world's most sustainable, rewarding, and promising sectors for economic development in the 21st century. Most of the countries on the Ring of Fire and in east Africa possess these two: unique ecological areas and geothermal resources. Although it is not a panacea, community-scale geothermal Tetrageneration™ could be the ideal solution in such a place. The environmental, social and economic benefits would be broad and far-reaching. The geothermal industry and international development would benefit from a comprehensive and thorough systems approach to the problem, including the use of full cost accounting to at least establish a lower bound on the value of so-called "intangibles".

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