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SUSTAINABILITY AND RENEWABILITY OF GEOTHERMAL ENERGY

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Terrestrial heat is a minor but significant component of the energy sector, and energy is one of the main factors upon which depends the socio-economic development of people on earth.
However, to become a permanent achievement for people, socio-economic development should meet two basic requisites: **ecological economics** and **sustainability**. Moreover, for certain forms of energy including geothermal, **renewability** comes into play.

GENERAL ASPECTS

According to some scholars who have speculated in recent years on economic development in the framework of environmental safeguard and resource sustainability [1, 2, 3], **ecological economics** is based on three inter-dependent parametres: *work*, *natural capital*, and *capital.produced by man*.

- *Work* includes any type of physical and mental effort made by people to meet their basic needs and to improve the quality of life;
- *Natural capital* consists of the whole of natural systems on earth (oceans, seas, rivers, lakes, air, flora, fauna, woods, underground and surface resources), including residues and wastes resulting from their exploitation. Therefore, the capacity by the natural systems to absorb and regenerate wastes and refuse materials should also be treated as a fraction of the natural capital;
- *Capital produced by man* is defined as the outcome of activities carried out to exploit the natural capital by gathering and processing natural resources of any kind (harvesting, farming, hunting, fishing, building, industry, electric generation, etc.), aimed at obtaining useful "products". Such "products" are not limited to material goods and profits only, but also include scientific and technological advancements aimed at beneficial effects on people, and the cultural and artistic wealth formed everywhere on earth;
- *Total capital* is the sum of the natural capital and of the capital produced by man.

In this context, the aforesaid scholars reject the deterministic approach of most classical economic theories (according to which development is ruled by the "invisible hand of the market"), and discuss the global economic development in the framework of the ecological complexity. They state that, in principle, there are two ways of conceiving development: *i)* by considering the capital produced by man as a "complementary fraction" of the natural capital (which means that the former depends tightly on the availabilty of the latter), or *ii)* by considering the capital produced by man as a "substitute" of the natural capital (which means that natural capital might even be sacked, upon the condition that a capital of equivalent value is produced by man). However, even though the two components of the total capital can vary, a value exists in both cases of the natural capital below which man is no more able to produce additional equivalent capital. As a consequence, the scholars in question conclude that such value represents a limit for the development.
Yet seen in a wider context, this conclusion recalls that reached by the Study Group of the Club of Rome in their report on the limits of the development due to finitness of the natural resources [4].

However, by considering sustainability in the light of both natural capital and environmental protection, the above-cited scholars go beyond the conclusions of the Club of Rome, and state that, to be effective, development should be pursued by maintaining the total capital at a given constant value. As a consequence, a suitable value of the total capital in each area should be fixed from time to time by: *i)* planning the upper exploitation limit for the various natural resources of the area; and

ii) establishing the capital produced by man within amounts compatible with the availability of such resources.
In short, the scholars cited above maintain that actual development can only occur where it is pursued in the framework of the ecological economics.

Sustainability is a concept describing "how" natural resources are harnessed and utilised by man; therefore, sustainability defines no intrinsic characteristic of any natural resource, but only reflects human decisions on how to exploit a certain resource in a given period of time, i.e. exploitation rate and technology applied to process and use it.
In this light, by rejecting an economic growth solely driven by the profit, Daly&Cobb [1] lay the foundations of a new ethics for the socio-economic development worldwide, which they call "solidarity with future generations", or "community with the future". To this purpose, they define two different forms of sustainability: *strong* and *weak sustainability*.

- *Strong sustainability* is attained when a given natural resource is exploited within fixed limits, enabling preservation and/or regeneration of a substantial fraction of it for use by future generations;
- *Weak sustainability* takes place when no exploitation limit is set for the aforesaid resource, upon the condition, though, that a substituting capital of equivalent value is produced by man.

Renewability, on the contrary, describes intrinsic peculiarity(ies) of a number of natural resources, which solely depend on certain continuous process(es) occurring in nature. However, since such process(es) take place with intensity and characteristics beyond man's control, in order not to deplete their original potential, the exploitation rate of renewable resources in a given period of time should be equal to their capacity of natural regeneration in the same period; in this case only we can speak of a fully sustainable development of such resources.

FACTORS CONTROLLING SUSTAINABILITY AND RENEWABILITY OF GEOTHERMAL ENERGY

Geothermal energy is a component of the natural capital, and should therefore be viewed in the framework of the general concepts outlined above. However, sustainability and renewability of this peculiar form of energy depend upon the following specific factors.

a) Temperature level

Even though geothermal energy refers to the total heat of the earth, when dealing with it for practical purposes, we should consider the only heat stored in, or extractable from rocks and fluids of, say, the upper 10 km of the crust; here, temperature may reach values of some hundreds degrees.

b) Heat transfer processes

Heat transfer within the earth's crust happens by three different processes: *i)* thermal conduction, *ii)* convection of fluids, and *iii)* advection of magma [5]. The first is a continuous but very slow process occuring everywhere on earth; fluid convection takes place in areas with favourable geological conditions, but may change notably in time (tens-to-thousands years); magma advection is a relatively fast process usually occuring in active volcanic areas and in areas at the collision margins of tectonic plates. Therefore, the "level of sustainability" and the "rate of renewability" of geothermal energy in a given area strongly depend on the geological conditions and the heat transfer process(es) of the area.

c) Resources, Reserves, and Time factor

A thiny fraction only of the heat contained in the upper 10 km of the crust is potentially amenable for extraction. In particular, by simplifying here the definitions given by Muffler-Cataldi [6] we can consider: *resource* the heat that *might* be harnessed from depths up to 10 km within a relatively long period of time (> 30 years); *reserve* the heat that *could* be tapped at market conditions from depths lower than, say, 3 km within a short lapse of time (< 30 years). This means that, when dealing with sustainability and renewability of geothermal energy, whatever the area concerned may be, we should always specify whether we speak of resources or reserves, and what is the exploitation period considered.

d) Heat extraction technology

The great majority (> 90%) of the heat in the upper crust of the earth is found in rocks and in closed pores of the rocks; therefore, the heat amenable for extraction through drilling is mostly that stored in fluids circulating in natural fractures. However, man-made rock fracturing can be applied in some cases to increase production of natural fluids (*stimulation*), and in other cases to inject water aimed at leaching an additional small fraction of the rock's heat (*HDR*). Man-made fracturing is thus a way to enhance the level of sustainability of the geothermal development in particular areas.

e) Carrier fluid and water recharge

To extract geothermal heat in massive quantities, a carrier fluid is needed, which consists of natural fluids contained in rock fractures and pores (steam, water, gas, or a mixture of them in various proportions); in these cases, if an appropriate balance is not reached between natural water recharge from nearby absorption areas and fluid produced by wells, a mass deficit of the reservoir fluid is likely to occur. In few other cases, though, injected or reinjected water can be used to recharge the reservoir and act as a carrier fluid, but also in these cases an appropriate balance should be attained between inflow and ouflow rates. In any case, however, if water recharge results in a temperature break-through alterating the original thermal regime of the reservoir, both energy sustainability and renewability of the geothermal field concerned may be negatively affected.

f) Reinjection

Reinjection of spent water and condensed steam from power plants enables disposal of undesirable chemicals and in slowering depletion of reservoir' fluid and pressure. Therefore, reinjection is another way to enhance the sustainability level of geothermal development in many areas.

g) Nature of reservoir fluid

Since most geothermal fluids contain dissolved chemicals, after production is started, scaling and/or corrosion phenomena often occurs (in the reservoir, well casings and surface plants), which may affect negatively the sustainability of geothermal development in a number of areas.

h) Time constant of heat resupply

Each geothermal system is characterised by its own thermal regime (heat flow density at surface, underground circulation, heat transfer process(es), and heat resupply from deep formations) which depends on the hydro-geologic, volcanological and tectonic conditions of the area concerned.; in particular, when no sudden geo-dynamic phenomena happen, heat resupply in each system occurs in a continuous and more or less constant way, with a specific "time constant". However, after fluid production is started by drilling, especially when massive quantities of heat are extracted, the thermal regime of the area may undergo remarkable modifications, which affects the original "time constant" of heat resupply from deep formations.

CONCLUSIONS

1. Sustainability of geothermal exploitation in a given area depends on decisions by the field developer concerning mostly: *i)* duration of the project; *ii)* rate and quantity of heat extraction; and *iii)* technology applied to tap, transport and use the natural heat. Therefore, if an appropriate limit is established for the quantity of heat to be tapped during the project period, geothermal can be considered a sustainable form of energy. However, the sustainability level may differ notably from case to case.

2. Renewability (natural resupply of heat), solely depends on deep geological processes, which are beyond any human control.

3. Sustainability and renewability thus reflect different concepts; nonetheless, they are inter-dependent from each other in that the level of sustainability may affect the rate of renewability, and viceversa, especially when massive quantities of heat are tapped in high-temperature areas.

4. Heat-extraction rate in a given area is in most cases much higher than heat-resupply rate. As a consequence, a notable deficit generally occurs in the total input-output heat balance.

5. On the other hand, since exploitation times of geothermal fields (in the order of 10-10^2 years) are very short as compared to the time necessary (>10^3 years) for the deep geological processes to regenerate fully the heat extracted, and taking also into account the different types of such processes as mentioned in point b) of previous chapter, generally speaking we can say that:

- conduction-dominated systems (*HDR*, for instance) may become in the future a sustainable energy source, but do not meet the requirements of a renewable resource;
- convection-dominated systems are a sustainable energy source (at a sustainability level, though, different from case to case), but in few places only represent a renewable resource;
- hydrothermal systems in areas where active igneous processes occur at shallow depth meet the requirements of being both a sustainable and a renewable resource;
- magma systems may become in the future a sustainable and renewable source of energy.

To sum up, geothermal is a sustainable energy source within limits to be fixed case by case, but in very favourable conditions only it can be defined a renewable resource.

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