Back to the Future: Towards Innovative Low and Zero Head Archimedean Hydropower Turbines in Irrigation Networks

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***Abstract*— The possibilities of exploiting low and zero-head potential of irrigation hydraulic networks and natural watercourses, for power generation in Europe and Greece, have both been given little attention. Such opportunities represent a large renewable energy resource which could be exploited by "modern Archimedean screw technologies" with inclined or horizontal axis. The present paper gives a brief history of rediscovering the old Archimedean screw pumps as a series of modern and efficient Archimedean hydropower turbines, including floating spiral screw devices, for harnessing the important and unexploited Greek small hydraulic energy potential of all the existing agricultural hydraulic networks and watercourses, producing useful green electricity. It gives a short view of the first Archimedean Inclined Axis Hydropower Turbines (AIAHT's) and of a modern Archimedean Water Current Turbines (AWCT's) results, which were carried out within the program ARCHIMEDES III recent research entitled "Rebirth of Archimedes: contribution to the study of hydraulic mechanics and hydrodynamic behavior of Archimedean cochlear waterwheels, for recovering the hydraulic potential of natural and technical watercourses, of maritime and tidal currents". Our analysis shows some very promising performances for such unconventional systems harnessing the important potential of a Pleiades of sites in the agricultural sector. In this paper are included series of innovating demonstration AIAHT and AWCT schemes, in cascade and in parallel, for low head sites in irrigation, drainage channels and watercourses and for series of horizontal floating screws exploiting the zero head kinetic energy of open channels and rivers, as good examples for jumping between the past and future and proving the importance of the "back to the future" rediscovering the Archimedean ideas, during the nowadays Era of Transition in Greece.**

Keywords—Archimedean screw turbines; small hydro; irrigation networks; kinetic energy

I. Introduction

Nowadays, in the time of transition, oil prices soar and global warming and climate change threatens, the need for affordable sustainable solutions to the energy and economic crisis around the world is ever increasing and encourage researcher to pay attention in founding new sources of green energy. The profound roots of the Archimedean hydraulic ideas and screw technology had been lost in the forgotten legacy of the mythology and of the agricultural beginnings, when man has both manipulated and harnessed the energy of all natural water resources. In the form of mechanical energy, small hydro has been for many centuries used for conveying water from rivers, the falling energy of which turned wheels for grinding wheat into flour. In a very strange and full enigmatic hydropower meaning ancient epigram, in "Anthologia Palatina Graeca", the Augustan poet Antipater of Thessalonica magnified the waterpower, the hydro-devices, the strange waterwheels of Olympus and probably of the Nezeros – Askouris Lake area, the Greek water deities and the nymphs: "Rest your wheel-turning hand, you maidens who grind. Sleep on even when the cock's crow announces down, for Demeter has resigned to the nymphs the chores your hands performed. They leap against the very edge of the wheel, making the axle spin which, with its resolving cogs, turns the heavy pair of porous millstones from Nezeros. We once again, have a taste of the old way of life, if we learn to feast on produce of Demeter without toil". Besides and beyond this poetic and with a certain ambiguity technical description of an efficient hydropower device, giving one of the earliest references to waterwheels and probably to water screws, it seems that Archimedean hydraulic screw technology had a very long history in Greece and in the world. Everything started 23 centuries ago, during Hellenistic time, in the technological context of Macedonian Alexandria, in the famous Library and Museum, where the spirit of Alexander the Great and Aristotle's was present, with various machines and mechanisms, gears, planetaria, celestial globes, the Antikythera Mechanism, with pumps, various mills driven by water wheels etc (Stergiopoulou and Stergiopoulos), (2009) [1,2]. The oldest hydraulic machine, still remaining in operation, is screw pump. Its discovery is attributed, on the basis of numerous Greek and Latin texts, to the greater perhaps engineering and mathematical genius of antiquity and all times, Archimedes of Syracuse in the 3rd BC century. The Roman engineer Vitruvius gave a detailed and informative description of the construction of an Archimedes Screw Pump (ASP) in his monumental engineering project "De Architectura" and since then, the classical description of the screw continues to contribute greatly to making it the most famous hydraulic device worldwide. (Stergiopoulou and Stergiopoulos, (2009) [1], (2010) [2]. At present, renaissance is taking place in the promotion and construction of various types of small hydro plants including the low and very low head cases and we are actually witnessing a new revolution in Archimedean small-hydro. The evolution of the spiral hydraulic screw mechanisms continues nowadays thanks to the overtime-continuous Archimedean contribution (Rorres), (2000) [3]. A view of the famous Archimedean screw with eight blades, as described by Vitruvius, a three bladed screw scheme, two farmers using a conventional manual screw pump to irrigate their farmlands in the Nile delta of Egypt, and two modern Archimedean Screw Turbines (AST), one Archimedean Inclined Axis Hydropower Turbine (AIAHT) and one Archimedean Water Current Turbine (AWCT), newly developed under the present ARCHIMEDES III research, are shown in Figure 1, trying to bridge the knowledge gap between the past and the present and proving the importance of the "back to the future" rediscovering the Archimedean ideas. In the same figure is also given a panoramic view of the ancient small lake Nezeros in the Olympus Mount, playing a key role into the Antipatros epigram and having an important drainage canal, presenting a certain small hydro interest. (Stergiopoulou and Stergiopoulos), (2010) [2], (2011) [4].

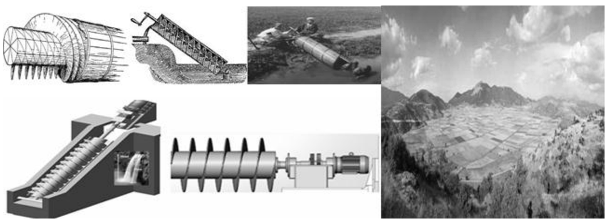

Fig. 1. Depictions of Vitruvius ASP, of modern AST and a view of the ancient Nezeros Lake.

II. Towards the Rebirth of Archimedean Screw Technology

Thousands of years after the original invention of the first cochlear rotor, the Archimedean Screw Pump (ASP), as the best known of all pumps, persists into modern times (Rorres), (2000) [3]. During the last years, the inverse use of the Archimedean screw, as a kind of inverse screw pump-turbine, is under discussion within the hydropower scientific community (Kantert), (2008) [5]. The screw renaissance taking place actually throughout the world in the promotion and construction of renewable energy valorizes Archimedean Screw Turbines (AST) for low, ultra-low and zero-head small hydro plants. Some cochlear inclined axis small hydro plants were installed during the last decade in Central Europe by various industrial companies, which were based on the inversion of the energy flow in their pumps operation and turning the old screw pumps into new screw turbines (Lashofer), (2014) [6]. Low, ultra-low and zero-head cochlear hydropower plants are developing very slowly, due to the fact that recent Archimedean screws are a new type of turbines in all countries throughout the world. Actually, a series of various experimental and theoretical efforts had been made under the research program ARCHIMEDES III, concerning various AST configurations, by using small-scale models, in order to proceed in the exploitation of small hydropower potential in various small-head river sites (Stergiopoulou and Stergiopoulos), (2012) [7]. For sites with relative greater heads, and relative greater water flows, the cascades of two or more similar energy spiral rotors in series and in parallel could give efficient Archimedean hydropower solutions. Figure 2 gives photorealistic views in "virtual sites" of inclined and horizontal axis Archimedean Screw Small Hydropower Turbines, in series and parallel. Also, this figure shows an Archimedean Turbine Park, having 4 inclined and 4 horizontal Archimedean turbines. The proposed "rebirth" of the Archimedean screw, as a modern hydropower tool, could cover various hydropower requirements of hundreds of sites in man-made open channels, in closed pipes having a small head and also in natural watercourses. Two inclined axis Archimedean screws inside water ducts are illustrated in this figure. The first case concerns a buried screw of some KWs minimizing landscape impact. The installed capacity P (KW) of some Archimedean screw turbines, in function of the water flow Q (horizontal axis) and the available height H (vertical axis), is also given in the same figure.

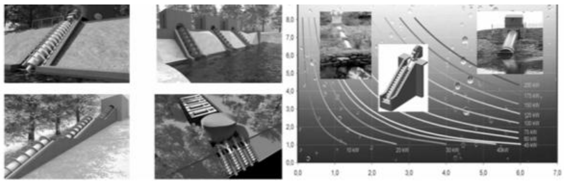

Fig. 2. Four Archimedean artistic photorealistic views for "virtual sites" and evolution of the installed capacity of AST, in function of Q and H

III. Towards the Macedonian Phalanx Archimedean Hydro Development of Greece

The important role, mainly of Pindos Mountain Range, controlling the annual rainfall difference between the North-Western and the Eastern Greece is obvious. It is also obvious the small hydroelectric potential role of the same mountain range with a series of other mounts (e.g. the Vermion, Olympus, Athos, Vardousia, Taygetos etc.). The very significant untapped hydrodynamic potential, of about 30 TWh according to an inventory, the current Greek economic crisis situation and all systematic efforts relative to the hydrodynamic behavior studies of innovative low and zero head Archimedean screw turbines could give an increased impetus in low head hydraulic renewable energy sources. According to the under evolution

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research, within ARCHIMEDES III program, the cochlear screws could find very promising modern applications, as efficient hydraulic turbomachines (Stergiopoulou and Stergiopoulos), (2011) [4], (2012) [7]. Pleiades of promising small hydro sites in Greece are presented in the Figure 3, in which is also given a “2 Hydro Spears Macedonian Phalanx” representation, with the important small hydroelectric role of Pindos mountain range, along the first Archimedean spear, from Epirus, Thessaly, Central Greece, Peloponnesus, and the role of the mounts of Vermion, Veras, Paikon, Rodope of Northern Greece, Macedonia and Thrace, along the second Archimedean spear. It is important to note that the two spears Macedonian Hydro Phalanx characterize the hydropower development of Greece, including the first hydropower stations being in operation since 1954 in Agras, Louros, Ladon and the larger hydropower stations in Central Macedonia, in Thrace, in Thessaly and in West Central Greece. The two long hydropower spears of this Macedonian development phalanx could be a real offensive Archimedean hydropower development tactic formation of Greece against the present crisis and a source of future hydro-economic prosperity as the glorious hydro-prosperity of the recent past. The same figure gives also a schematic representation of one AST with inclined shaft exploiting the potential of a watercourse having a flow discharge Q and a height H.

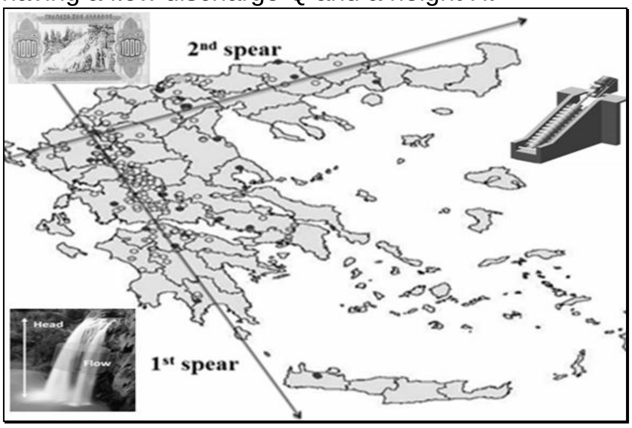

Fig. 3. The “2 Hydro Spears Macedonian Phalanx Archimedean Hydro Development” of Greece

For such a Greek Archimedean small hydropower development effort, mainly along the “North-South Small Hydropower Development Spear”, series of questions to be answered are real technical dilemmas. These dilemmas are illustrated in Figure 4. First dilemma: what are more efficient, Archimedean screws in series or in parallel? Second dilemma: if we have a site with screw in series how many screws should be connected? Third dilemma: if we have a site with screws in parallel how many screws should be connected? Fourth dilemma: if we have a site with the combined solution of screws in parallel and screws in series how many screws should be connected for each case?

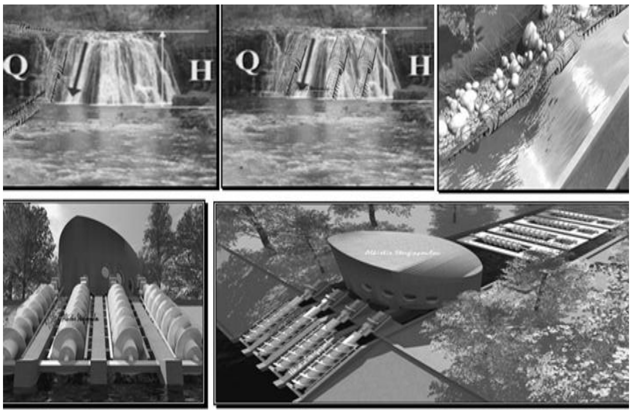

Fig. 4. First, second, third and fourth Archimedean screws dilemma

For a particular AST case study, concerning a first site, in the Drainage Channel 66 (figure 5), in Imathia Prefecture, the maximum flow of the screw turbine is estimated to be 4.67 m^3/s. The net head is calculated by estimating the hydraulic losses or after assumption of 3% head losses. The gross head was 1.50m. Then the net head becomes 1.45m. The generated power on the turbine axis is P_t=49.821 KW (with η_{turb}=0.75) and the generated electrical power is P=41.501 KW (with η_{gen}=0.98 and η_{gear}=0.85). It is estimated that the AST would be operated at the maximum power of 41.501KW with a design flow approximately at least 4.67 m^3/s in the river for 150 days per year. For the rest of the year the turbine would be operated with reduced power. The annual energy production is estimated on the basis of the capacity factor CF = time of design operation/8760h. In our case, CF is around 0.65. The annual energy production E(KWh)=P(KW).CF.8760 is calculated E(KWh) = 236 307 KWh/year. A first estimation of the installation cost gives a total amount of 121 000 E, with 58 000E for the equipment of AST, turbine and generator, 40 000E for the civil works, 15 000E the electrical system and the connections, 8 000E other. A quick first economical analysis would probably give a very interesting P.P. (payback period) of 5-6 years, a very good N.P.V. (Net Present Value) and an efficient I.R.R. (Internal Rate of Return). In general AST power development in this particular site is good idea for investment in Archimedean green energy.

The third type of hydropower turbine concerns the low and zero head Archimedean screw systems with inclined and horizontal axis efficient and technically feasible machines.

Fig. 5. A general view of a first site of the drainage channel 66 for a possible AST future development

For a second site, in the Tripotamos river catchment area, near the town of Veria, for a future Archimedean Small Hydro exploitation, with H=2.34m and the flow variation curve (Q(m3/s), t=days) illustrated in figure 6, the river F.D.C curve and the useful F.D.C. curve in common with a preliminary study propose a final Archimedean plant, with nominal flow 2 m3/s, efficiency of the screw turbine 84.75 %, efficiency of the generator 93 (%), efficiency of the multiplicator 91.2(%), installed power P=33 KW, and energy produced per year E=107 976,8 KWh.

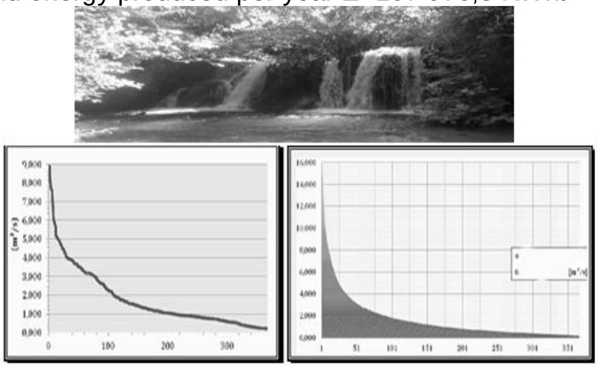

Fig. 6. A site for an Archimedean Small Hydro exploitation with F.D.C curves.

For a third site, in the Arapitsa River catchment area, near a small irrigation weir, downstream of the town of Naoussa, a potential future Archimedean Small Hydro exploitation for H=4.68 m and the previous same flow data, should be based probably on 2 similar screw turbines in series (Figure 7). The total installed power P = 2 x 33 = 66 KW and a yearly produced energy E= 2 x 107 976,8 =215 953,16KWh.

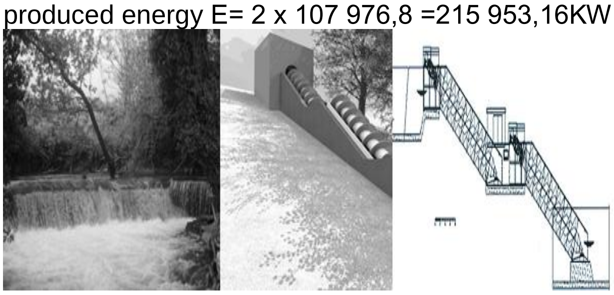

Fig. 7. Typical schemes with two AST's, in series, in one irrigation weir in Arapitsa

For a fourth site, in the drainage channel 66, with a head of 2.34m and a design flow 4m3/s, it is possible to install in parallel two similar screw turbines, having an individual hydrocapacity of 33KW and a yearly productivity of 107 976, 8 KWh giving a total install capacity of 66 KW and a total yearly energy production of 215 953,16KWh

IV. A SHORT VIEW OF RECENT A.S.T. RESEARCH FOR A.I.A.H.T. & A.W.C.T.

Various innovative small-scale models of new Archimedean Screw Turbines (AST's) were designed, and developed in the framework of the research program of ARCHIMEDES III. During the last years a series of extensive ARCHIMEDES III research experiences had been made in an open flume hydraulic experimental channel, concerning initially various, small-scale AIAHT's (Archimedean Inclined Axis Hydropower Turbines) configurations. Two representative Archimedean experiences in an open flume channel for two inclined axis AST are schematically illustrated in the Figure 8, together with the first experimental results (efficiency η in function of flow ratio Q/Qo, with Qo the design flow) relative to a third AIAHT closed circuit integrated hydropower plant.

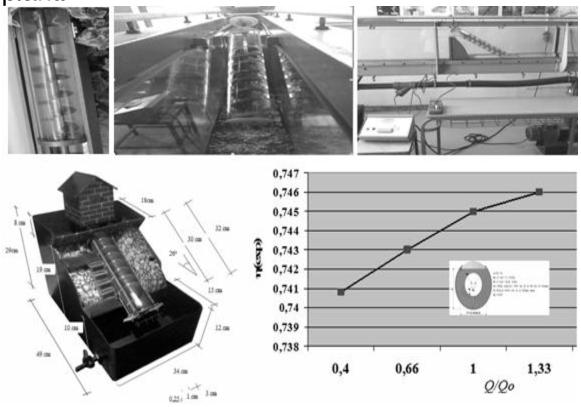

Fig. 8. Three innovative small-scale models Archimedean spiral rotors developed in the framework of the research program ARCHIMEDES III.

Recently three other new 2-bladed AIAHT, of the same length 30.5cm, the same input diameter 5cm, with an output diameter 9.4cm and three step ratio S/D=1, 0.8 and 1.2, were developed and are under experimental exloitation in the framework of the same research program (Figure 9).

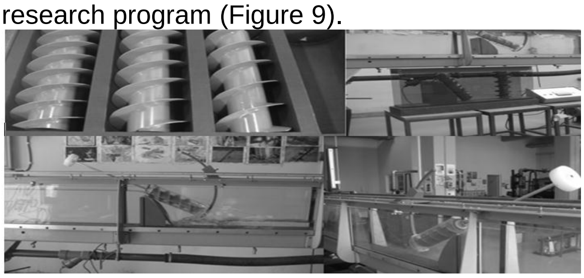

Fig. 9. New AIAHT's representative ARCHIMEDES III experiences

The possibility of exploiting kinetic hydraulic energy of irrigation and drainage hydraulic networks, and currents of technical and natural watercourses, for power generation, have both been given little attention, although such currents represent a large renewable energy resource which could be exploited by "modern Archimedean screw technologies". A series of AWCT photorealistic views, with horizontal axis floating screws for the Greek natural and irrigation man-made networks are presented in figure 10. In this figure are given the geometrical characteristics of the new horizontal Archimedean Screw Turbine recently installed and experimented in the hydraulic channel of the Laboratory of the Institute for Water Management, Hydrology and Hydraulic Engineering, in Vienna (Mayrhofer and Stergiopoulou et al), (2014) [8] with the dimensions $L_{channel}$=10m, $b_{channel}$=1.4m, $h_{channel}$(depth)=1m. Some photorealistic views of floating AWCT's are given in the same figure.

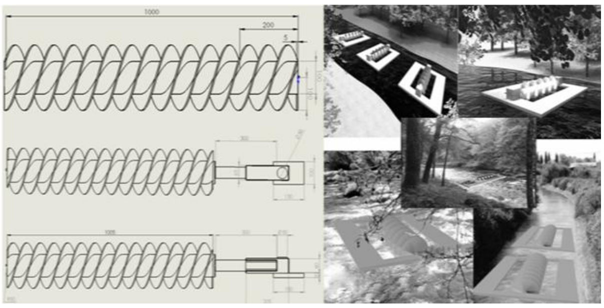

Fig. 10. Design of a new developed horizontal screw rotor with photorealistic views of floating screws

The length L, the diameters (output and input), the pitch S and the number of blades of the developed new screw rotor are: L=1m, D_o=200mm, D_i=100 mm, S/Do=1, S=200mm, n=3 (number of blades). The horizontal screw could rotated horizontally and change direction ($\Delta\theta$ = 100^o), forming an upstream angle of 50^o with its initial position and a downstream angle of 50^o with its initial position (see Figure 12). Some information concerning two possibilities for the rotation of the horizontal screw is given in the same figure.

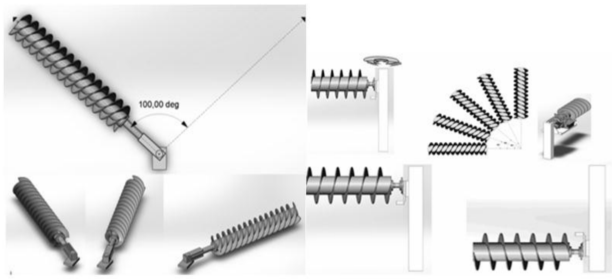

Fig. 11. Rotation possibilities of an innovative horizontal screw

An artistic photorealistic view of a series of horizontal screw rotors in a channel is given below in Figure 13 together with the new 3-bladed horizontal axis Archimedean screw turbine, before installing in the experimental channel of the Laboratory the Institute for Water Management, Hydrology and Hydraulic Engineering, in Vienna (Mayrhofer and Stergiopoulou et al), (2014) [8]. On the right edge of the screw axis is the torque meter.

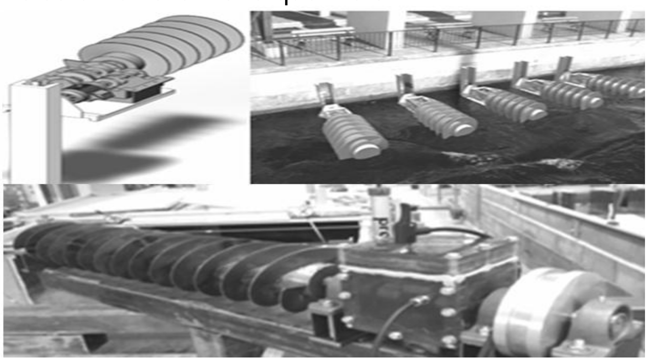

Fig. 15. Artistic photorealistic view of a series of horizontal screw rotors in a channel & a view of the innovative 3-bladed horizontal axis Archimedean screw turbine

Some other views of this new horizontal axis Archimedean screw turbine installed recently in the long channel of the Laboratory the Institute for Water Management, Hydrology and Hydraulic Engineering, in Vienna, are given in the Figure 14 (Mayrhofer and Stergiopoulou et al, 2014). Now, the torque meter is on the left edge of the screw.

Fig. 12. Views of the new 3-bladed horizontal axis Archimedean screw turbine inside a long channel

V. Preliminary Conclusions

The presented here brief history of rediscovering the old Archimedean Screw Pumps (ASP) as a series of modern efficient Archimedean Screw Turbines (AST) and the experimental and theoretical contributions to the development of various new inclined and horizontal axis screw turbines prototypes, together with the preliminary ARCHIMEDES III research efforts, proved the very promising and very useful exploitation of two types innovative screw techniques, under the form of Archimedean Inclined Axis Hydropower Turbines (AIAHT's) and Archimedean Water Current Turbine (AWCT's). Hundreds of these two types screw devices along the “2 Hydro Spears Macedonian Phalanx” could harness the important unexploited low, ultra-low and zero-head Greek hydraulic potential of a Pleiades of sites in the agricultural sector, in irrigation and drainage man-made networks and natural watercourses and recovering the flowing kinetic energy of streams and open channels as well. Such innovative Low and Zero Head Archimedean hydropower turbines in Irrigation and Drainage Networks, with AIAHT and AWCT cochlear hydropower devices, seems to prove the importance of the “Back to the Future” rediscovering the old but always modern Archimedean ideas, tend to emphasize jumping between the past and future and find the most reliable sustainable development way of Greece through the obstacles of the actual Era of Transition.

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