SOLAR HYDRO ELECTRIC POWER PLANT

FIGURE 1

(57) Abstract: Solar Hydro Electric power plant is the new power plant that comprises the modified reversible hydro electric power plant (3–10) operating together with the photovoltaic power plant (1). Such power plant assembly, called Solar Hydro-electric Power Plant uses solar energy as the only input for production of solar and hydro energy. Thereafter, water reservoir (6) seizes for daily and seasonal energy storage, thus basically solving the problem of energy storage, which is the biggest problem of wider use of solar energy. The presented Solar Hydro Electric power plant for now represents the only permanently sustainable energy source that can continuously provide power supply to a consumer, using exclusively natural and renewable energy sources, without causing harmful effects on the environment.
SOLAR HYDRO ELECTRIC POWER PLANT

DESCRIPTION OF INVENTION

1) AREA TO WHICH THE INVENTION RELATES

This invention relates to the new self sustainable source of electric energy which includes solar electric power plant and hydro electric power plant (the name solar hydro electric power plant is derived from it), intended for continuous electric energy supply of a consumer (house, settlement, town, island, region, factories etc.) from renewable energy sources. Thus, the new energy source which uses only renewable energy sources could contribute more significantly to the share in energy balances of various countries.
2) TECHNICAL PROBLEM
(for whose solution patent application is required)

Providing larger and larger quantities of energy, necessary for economic growth of every country, is evidently a problem nowadays. On the other hand, over 70% of atmosphere pollution caused by carbon dioxide (and other greenhouse gases) comes from the energy sector, causing immeasurable negative effects on the climate (global warming, etc.).

Solar energy has the biggest exploitation potential of all renewable energy sources. The transformation of solar into electric energy by the so-called photovoltaic systems, i.e. photovoltaic generators, is particularly interesting for this invention.

However, the problem of wide use of solar energy is connected to relatively high price of solar systems on one hand, and on the other, with interminated solar radiation. While the costs of solar photovoltaic systems gradually decrease from day to day (particularly with production increase and technology development), its storage during the periods lacking solar energy remains the biggest problem. Namely, the existing solar photovoltaic power plants can't independently supply a consumer, but only give electric power to electric power system when solar energy is available.

Therefore, the problem of finding the technical-technological solution using renewable energy sources for continuous power supply to a consumer is obvious. A consumer can vary from a residential unit (house), small or big settlements, factories, islands, towns, the electric energy supply of a whole country from renewable energy sources.
3) THE STATE OF TECHNICS

(presentation and analysis of known solutions of the defined technical problem)

Up to now there was no technical solution to the problem. There are solar photovoltaic power plants and reversible hydroelectric power plants.

In this patent application they are combined in an original way into a single system called Solar Hydro Electric power plant, which can independently and continuously supply a consumer with electric energy and power, unlike the mentioned power plants (only solar photovoltaic and only reversible hydroelectric power plants).
4) THE ENTITY OF THE INVENTION

(in order to understand the technical problem and its solution and quotation of technical innovation in relation to previous state of technics)

The proposed sustainable power plant is in its basic concept a reversible hydroelectric power plant that uses the PV power plant 1 instead of electric energy from the network to activate the pumps 4, and instead of one, has two separate pipelines, one for pumping 5 and the other for taking water to the turbine 7. Namely, the PV power plant transforms solar into electric energy which pumps water from the available source 10 into the reservoir 6 located at higher levels. Water from the reservoir 6 is then used in the hydroelectric power plant 8 and 9 for production of electric energy.

On the other hand, water in the reservoir 6 is accumulated for the periods lacking solar radiation, so that in those periods electric energy can be produced on the turbines 8 and transferred to electric network of a settlement or local consumer. In this way the reservoir 6 serves as daily and seasonal storage of energy obtained from the PV power plant 1 during sunny weather, thus providing solution to energy storage, which is the biggest problem of wider use of solar energy.

The operation of this system implies achieving full independence of electric energy supply to a consumer, which is basically obtained from solar energy. The proposed power plant - system is sustainable on every location and does not have harmful effects on the environment, because it is based exclusively on exploitation of renewable energy sources, using water as the main resource that generates continuous production of energy. The formed reservoir 6 and appertaining hydro electric power plant 8 and 9 are very flexible in operation and energy production, therefore can adjust very easily to the consumers' needs, unlike the PV power plant 1, whose operation and production depend on solar radiation. The combination of these two power plants creates a new type of power plant suitable for continuous production of electric energy.

The main characteristic of the new Solar Hydro Electric power plant is that it is not limited by the size, so that the smallest and the largest units can be used, i.e. for supply of a residential unit of a few hundred kilowatts to powerful plants of tens and hundreds megawatts.

This invention explains the new concept of exploitation of solar and hydro energy in an original way that takes into account the advantages of each. The hydroelectric power plant 6 and 9 is used for continuous production of energy and solar energy is primarily used for creating hydro potential, i.e. for water storage for production of hydroenergy. Solar energy (PV generator 1) is used to pump water from the lower level 10 (reservoir, aquifer, sea, lake, river) into the upper level, where it is
stored in the reservoir 6. The stored water is used for hydroenergy production in accordance with the formed hydropotential (height difference) on the turbine 8 from where water is discharged into water resource from which it is pumped by pumps 4 driven by the PV generator 1, Fig. 1. In this way same water is used continuously, flowing within the artificially created, closed hydrological cycle. The available upper reservoir 6 is, actually, stored solar energy, available for continuous use on turbine 8 (during night and day), according to the consumers' needs.

The proposed power plant is a local energy source that can be built in direct vicinity of the place of consumption, providing that all required conditions exist, which is very favourable, because energy doesn't have to be transported. The prerequisites for operation of this power plant are periodical insolation, water and elevation difference between the upper and lower water level, where gravity effects - hydropotential, is exploited. Hydropotential can be created according to topographical features of the ground, wherever there is ground-hill elevation difference. However, artificial hydropotential can be created anywhere, by constructing an appropriate structure with elevation difference between upper and lower water level. This means that smaller or larger hydropotential can be created anywhere, naturally, at different costs. In addition to the necessary elevation difference, where gravity activity can be utilized, water is required to drive the turbines.

The system can be smaller or larger, open (Fig. 1) or closed (Fig. 2), i.e. with more or less water loss. The transportation part of the system 5 and 7 is always closed. It consists of pressure pipes that convey water from the lower to the higher level 5 and the hydroelectric power plant pressure line 7. Reservoirs can be closed or open. All big systems are, as a rule, open, whilst small systems can be constructed as closed. Theoretically speaking, water is necessary only for filling the system and compensating the losses from the system. It is optimal when filling and compensation can be achieved from natural resources, by rain or rainwater from the local drainage basin, or water from the local watercourse, groundwater and sea. Losses occur due to evaporation and water leakage from the reservoir (upper 6 and lower 10). Evaporation, and particularly leakage, from the reservoir can be significantly reduced or eliminated by appropriate engineering measures.

Local natural characteristics, climate, water resources, topography, geology, etc. represent the framework for construction of the power plant and for its efficiency. It is important to stress that the power plant is sustainable and that it can produce electric energy as long as there is solar radiation and gravity. The price of energy depends on a whole range of elements and profitability depends on the price of the competing classical sources. It is still to be expected that classical energy sources (thermal and nuclear power plants) are more competitive, regardless the fact that energy is pure and renewable. However, taking a long-term view, it is to be expected that classical energy sources will be more expensive, so that the proposed power plant will be more competitive and cost effective. When long-term sustainability of energy production is required, utilizing only
renewable, pure natural resources, the proposed Solar Hydroelectric Power Plant is without competition.

In Solar Hydro Electric power plant it is very important to determine the power of the PV generator 1 which is the most expensive element. The upper reservoir 6 has the most important role here. It enables water accumulation over a long period of time and, therefore, hydroenergy production, which enables bridging over the period when the PV generator 1 input is lower or absent.

In this way the PV generator 1 is selected according to the critical one-year period out of a number of years, so that the minimum of maximum power is selected, required for continuous production of hydroenergy in critical periods (required water quantity) and selected levels of operation security (additional water quantity in reservoir for incident and unforeseen situations). The system is more effective if water that can be used, i.e. diverted towards the reservoir, exists upstream of the upper reservoir 6, because the reservoir 6 is filled naturally, not only by pumps, which would result in smaller capacity of the solar photovoltaic power plant 1 for a corresponding value. The system will also be more effective if a part of solar energy, produced in periods of strong solar radiation, is directly used by consumers, because the reservoir volume 6 and the capacity of the pumping system 3 and 4 and PV generator 1 will then be smaller.

The construction costs of the reservoir (upper 6 and lower 10) also affect the total price of construction. Various combinations are possible thereat. It is most favourable when there is no need for construction of the lower reservoir 10, which is the case when the capacity of water resources used for water intake exceeds the needs (e.g. when sea, big river or aquifer represent lower accumulation 10) and the construction of the upper reservoir 6 is simple and inexpensive, or in the case when such reservoir-lake already exists. In principle, the bigger the available drop (potential energy), the more cost-effective the hydroelectric power plant 8 and 9. However, in this case, a stronger PV generator is required in order to pump water into the reservoir 6.

The proposed power plant has big advantages due to the local electric energy source that does not require any fuel or significant transport of energy to the consumer. This means that energy can be produced and consumed at isolated locations, far from transport and supply lines (on islands and
similar). In this way the transport system construction costs and energy losses that occur due to energy transfer are reduced. On these locations the power plant can already compete with classical energy sources, as it does not require construction and costs related to transport or any fuel. The power plant can be constructed at any location with water resources, but without the required hydropotential. This potential can be artificially created using the PV generator 1 and local topography of the ground.

This type of power plant is particularly suitable for the supply of special consumers, such as isolated military bases, important strategic structures on isolated locations etc., because it is entirely sustainable locally.

The Solar Hydroelectric power plant is for the time being the only permanently sustainable energy source that can provide continuous electric energy supply to a consumer, using only natural and renewable energy sources, without harmful impacts on the environment.
5) A BRIEF DESCRIPTION OF DRAWINGS

The accompanying drawings included in the description, which are a part of the invention description, present the best way of invention realization and provide help in explaining the basic principles of the invention.

Fig. 1. Diagram of Solar Hydro Electric power plant (open type).

Fig. 2. Diagram of Solar Hydro Electric power plant (closed type).
6) DETAILED DESCRIPTION OF AT LEAST ONE WAY OF REALIZATION OF THE INVENTION

This part contains details of the supposed realization of the invention, whose basic example is shown in the attached drawing.

Solar Hydro Electric power plant comprises the following elements:

1) Solar photovoltaic power plant (photovoltaic generators),
2) Inverters (transform DC into AC, includes the so-called maximum power trackers),
3) Electro motor,
4) Pump,
5) Pipeline that raises water from upper level of lower reservoir to upper reservoir,
6) Upper reservoir,
7) Pipeline that lowers water from upper reservoir to upper level of lower reservoir,
8) Turbine,
9) Generator,
10) Lower reservoir (sea, big river, aquifer etc.)

Solar Hydro Electric power plant operates when solar energy is by solar photovoltaic generators 1 transformed into electric energy, required for supply of electro motor 3. However, if the electro motor is AC, the DC electric energy from the photovoltaic power plant is by inverter 2 transformed into AC. Inverter 2 includes the maximum power tracker that matches the load (electro motor 3) to the power of the photovoltaic power plant 1. Electro motor 3 drives pump 4 that pumps water from the upper level of the lower reservoir into upper level of the upper reservoir 6. This transport is done by means of pipeline 5. Pipeline 7 conveys water from the upper reservoir to the turbine 8 that drives the generator 9. After that, water is transported towards the lower reservoir 10, i.e. sea, big river, aquifer etc.

There are two most important elements of the proposed solution: PV generator 1, without which there is no hydropotential, and reservoir/storage 6 for storing water i.e. solar energy for production of hydroenergy when the PV generator 1 is out of function. As the PV generator 1 is still the most expensive element, the aim is to reduce its size to the possible minimum. Therefore, in addition to the technological solution of the Solar Hydro Electric power plant, proper sizing of the system is
very important so that it will fully meet the consumers' needs for electric energy throughout the whole year. In that sense, the following calculation should be used:

A) Electric power of HE power plant 8 and 9

Hydro energy, generated by the reservoir, can be calculated according to

\[ E_{\text{H(gross)}} = \rho \cdot g \cdot H \cdot V \ (J, Ws) \]  

(1)

and hydro accumulation power:

\[ P_{\text{H(sross)}} = \rho \cdot g \cdot H \cdot Q/s, \Psi ) \]  

(2)

where \( V \) (m\(^3\)) is water volume in reservoir, \( H \) (m) is elevation difference between the lower and upper water level, \( g \) (m/s\(^2\)) is gravity acceleration, \( \rho \) (kg/m\(^3\)) is water density, and \( Q \) (m\(^3\)/s) is flow.

Therefore, the accumulated water, i.e. reservoir size \( V \) (m\(^3\)) and the available height difference \( H(m) \) determine the energy production and installed turbine capacity \( Q \) (m\(^3\)/s) determines the power. Energy production is bigger when the accumulation and drop are bigger. Local conditions regarding reservoir construction (volume and elevation) will determine which combination of height difference \( H \) and water volume \( V \) is the better solution for the planned fulfilling of the consumers' demands - energy production. In addition, the selected drop \( H \) and flow \( Q \) will define the most efficient type of turbine. Net electric energy, produced by the hydroelectric power plant is:

\[ F_{\text{eH(HE)}} = \rho \cdot g \cdot H_n \cdot V \cdot \eta_{\text{tg}} \ (J, Ws) \]  

(3)

where \( H_n \) is net available drop, and \( \eta_{\text{tg}} \) is total available effect of turbine and generator (0.75 — 0.92).

B) Electric power of photovoltaic power plant 1

The selected reservoir volume 6 (required energy), height difference (total head) and available pumping time into the reservoir 6 define the required power of the PV generator 1.
By inserting water density/\(\rho\) and gravity constant \(g\) into Eq. (1), by converting the units and by using \(Q_{py}\) instead of volume \(V\), and \(H_{TE}\) instead of total head \(H\) (Fig.2.), total daily hydraulic energy, which the PV power plant 1 can produce at the outlet of the pumping unit, is obtained

\[
E_{H^{(MP)}} = \frac{2.12Q_{py}H_{TE}}{1000} \text{ (kWh)}
\]

where \(Q_{py}\) is average water flow (m\(^3\)/day) pumped from the lower into the upper reservoir, and \(H_{TE}\) is average total head (water level difference in upper and lower storage + losses) (m).

The starting equation for calculation of the required PV generator 1 power, \(P_e\) expressed in (W), in reference conditions (Standard Test Condition STC - instantaneous radiation 1000 W/m\(^2\), relative optical air mass AMI .5 and temperature of the PV generator 25°C), which establishes the relation between the output hydraulic and the input radiated energy, based on Kenna and Gillett, 1985 , assumes the following shape:

\[
r_{el} = \frac{100Q}{f_m[1-\alpha_cV_{cell}-T_0]} \eta_{MP} \cdot \frac{E_H}{E_s} \text{ (W)}
\]

where \(E_H\) (kWh/day) is the output hydraulic energy from the pumping system (1-4), \(E_e\) (kWh/day) is electric energy at the motor-pump unit input, \(f_m\) is load matching factor to the PV generator characteristics, \(\alpha_c\) is cell temperature coefficient (\(^\circ\)C\(^-1\)), \(T_0\) is referential temperature of the PV generator (1) (25°C), \(\eta_{MP}\) is motor-pump unit efficiency.

Therefore, the calculation of nominal electric power of the PV generator 1 is based on the known demand for hydraulic energy \(E_H\) and available irradiated solar energy \(E_s\) in critical period and the known efficiency of the motor-pump unit \((3\ and\ 4)\ \eta_{MP}\) in referential operating conditions, taking into account the effect of outside temperature on the efficiency of the PV generator 1.

By inserting Eq. (4) into Eq. (5), the equation for electric power of the PV generator 1 is obtained:
which will be used in this patent solution for calculation of electric power of the PV power plant 1.

\[ P_{el} = \frac{2.72 \cdot H_{TG}}{f_m [1 - \alpha_s (T_{cell} - T_0)]} \cdot I_{MP} \cdot E_{S} \cdot Q_{PV} \ (W) \]  

C) Water and energy balance

The reservoir volume, hydroenergy production and the power of the PV generator 1 and HE power plant 8 and 9 are determined by natural characteristics of the ground on one hand and on the other hand by the consumers’ needs for energy. The construction is intended for meeting the demands of a consumer, so the energy consumption regime is the key variable for sizing and operation of the Solar Hydro Electric power plant. In this paper the subject problem is solved at the level of the system as a technological entirety that equally comprises all system parts, including natural (climate, hydrology, reservoir 6, hydro generators 9 and PV generators 1), consumer needs for electric energy and other processes within the system, throughout the whole period of system operation.

Therefore, the system is analyzed as a whole, dynamically during the entire operating period, taking into account all changes that occur in relation to the available resources (capacity and needs) and energy production demands.

Climate and hydrology are the key components that determine water resources. Climate determines the water input in the reservoir 6 on the one hand, and solar energy availability on the other hand. Climate inputs are stochastic, therefore need to be treated accordingly throughout the entire period.

Figure 1 presents all water inputs (\( <2NAT(Q,R)_{(i)}\), \( Q_{PV(i)} \) and \( INF_{(i)} \)) and outputs (\( INF_{(i)}\), \( EV<3 \) and \( Q_{TG(i)} \)) from the upper reservoir 6 of volume \( F_{(i)} \), air temperature \( T_{d}Q \), maximum level of upper reservoir 6 \( H_{U}(Q5) \) difference between the lower level of upper reservoir 6 and upper level of lower
reservoir 10 (sea) $H_{\text{Res}}^\text{(O)}$ total height to which the PV power plant 1 must lift water into the upper reservoir 6 $H_{\text{TE}(O)}$.

Water balance and energy balance are typical for the system.

Cl) Water balance

The water balance in the system with only the upper reservoir 6, for a certain time period is:

$$V_{\text{in}} = F_{\text{out}} + V_{\text{losses}}$$  \hspace{1cm} (7)

where $V_{\text{in}}$ is water flowing into the upper reservoir 6, $F_{\text{out}}$ is water flowing out of the reservoir 6 and $V_{\text{losses}}$ are total water losses in the upper reservoir 6.

The aim is to reduce losses as much as possible, because it affects the system efficiency, i.e. the required power of the PV power plant 1.

In the event when lower reservoir 10 is also used, water losses in the lower reservoir 10 must be taken into account, therefore, the water balance in the system is:

$$V_{\text{in}} - V_{\text{losses,intake}} = V_{\text{out}} + V_{\text{losses,accumulation}}$$  \hspace{1cm} (8)

where $V_{\text{losses,intake}}$ are losses at intake and $V_{\text{losses,accumulation}}$ are losses in the upper reservoir 6.

In circulating system with open reservoirs 6 and 10, water must be compensated in the observed period $t$:

$$V_{\text{losses}} = V_{\text{losses,intake}} + V_{\text{losses,accumulation}}$$  \hspace{1cm} (9)

In case of limited water resources, losses must be reduced to a minimum. For the closed system $V_{\text{losses}} \approx 0$ is applied.

Changes within the system are described by the system state equation. The system state equation for the upper reservoir 6 is:
\[
 r_m = V_{it(i)} + Q_{PV} + Q_{NAT} + R_{i(j)} - EV_{i(j)} - Q_{dis}(i) + INF_{m(i)} \tag{10}
\]

Where increment \( i \) assumes the values \( z-1 \) to \( N \) (\( N \) is the total number of time stages, e.g. months, decades or days); \( F(j,i) \) and \( V(i) \) are reservoir 6 volumes in \( (z-1) \) and \( i \) period respectively \( (m^3) \); \( Q_{PV}(i) \) is water pumped by the PV power plant 1 in \( i \) period \( (m^3/day) \); \( R_{i(j)} \) is total precipitation coming into the reservoir in \( i \) period; \( Q_{NAT}(i) \) is natural flow from the adjacent watershed in \( i \) period; \( EV_{i(j)} \) is water from reservoir 6 consumed by evaporation in \( i \) period \( (m^3) \); \( Q_{dis}(i) \) is water discharged from the upper reservoir 6 into the turbine/generator unit 8 and 9 for producing electric energy in \( i \) period \( (m^3/day) \) and \( INF_{i(i)} \) is infiltration in \( i \) period \( (m^3) \).

The state equation at water intake is:

\[
 W(i) = W(i-i) - OPV(i) - P(losses,intake)(i) + Q_{inflow}(i) \tag{11}
\]

Where \( W(i-i) \) and \( W(i) \) are water volumes of the lower reservoir 10 in periods \( z-1 \) and \( i \) respectively. \( F(losses,intake)(i) \) are all losses at water intake 10 in \( i \) period, and \( Q_{inflow}(i) \) are all water inflows to the intake 10 in \( i \) period. The type and characteristics of intake will determine which variables will describe these processes. For example, in case of sea intake 10, both variables, as well as changes in volume, are insignificant. However, in case the reservoir 10 is used, the equation is the same as for the upper reservoir 6.

The total water balance in the system also includes water quantity in pipelines 5 and 7, which is very little in relation to water in the reservoir 6.

\textit{C2) Energy balance}

Based on the aforesaid, the total energy balance for a given period (e.g. one year) in the Solar Hydro Electric power plant system can be expressed with relations (a) to (i), i.e.
(a) Total electric energy, produced in the PV power plant 1 from radiated solar energy, can be calculated by the equation:

\[ E_{el(PV)} = \eta_i - VrA \cdot E_S \]  

where \( \eta_i \) is PV generator 1 efficiency, \( \eta_i \) is inverter 2 efficiency (as well as the complete electronic unit for conditioning power of the PV power plant 1 to load), \( A_e \) is the PV generator 1 area and \( E_S \) is radiated solar energy.

(b) This electric energy is divided into:

\[ E_{ei(PV)} = E_{ei(MP)} + E_{ei(overflow)} \]  

where \( E_{el(PV)} \) is total electric energy produced by the PV power plant 1, \( E_{el(MP)} \) is electric energy consumed by the motor pump unit 3 and 4 operation, and \( E_{ei(overflow)} \) is excess electric energy sent to the electric power network if the Solar Hydro Electric power plant system is connected to it.

Naturally, the excess electric energy is not necessary for achieving energy independence of a consumer, but it occurs because it is not possible to select the size of the PV power plant 1 that will, in every period, produce the exact quantity of energy which the consumer needs; but in some periods this excess, which cannot be received by the upper reservoir 6, is bound to occur.

(c) Total available hydraulic energy \( E_{H(cumulative)} \) in the upper reservoir 6 is:

\[ E_{H(accumulation)} = E_{H(MP)} + E_{H(IN)} - E_{H(losses)} \]  

where \( E_{H(MP)} \) is hydraulic energy from the motor pump unit 3 and 4, \( E_{H(IN)} \) is hydraulic energy of water inflow, and \( E_{H(losses)} \) are marked hydraulic energy losses within the system, that can be calculated as follows:

\[ E_{H(losses)} = E_{H(losses,intake)} + E_{H(losses,accumulation)} \]  

(15)
where \( E_{H(iosses,intake)} \) are hydraulic energy losses at intake, and \( E_{H(iosses,accumulation)} \) are hydraulic energy losses in upper reservoir 6.

(d) The connection between hydraulic and electric energy of the motor-pump unit 3 and 4 can be expressed:

\[
E_{H(MF)} = \eta_{MP} \cdot E_{el(MP)}
\]

where \( \eta_{MP} \) is pumping unit efficiency (motor/pump 3 and 4).

(e) The connection between electric and hydraulic energy of the turbine/generator assembly 8 and 9 can be expressed:

\[
\eta_{TG} = \eta_{TG} \cdot E_{H(accumulation)}
\]

where \( \eta_{TG} \) is turbine/generator assembly 8 and 9 efficiency, and \( E_{el(HE)} \) is total electric energy produced by the HE power plant 8 and 9.

(f) If \( \eta_{el(MP)} \) from Eq.(13) is expressed explicitly and inserted into Eq.(16),

\[
E_{H(MF)} = V_{MP} \cdot \left( E_{el(PV)} - E_{el(overhead)} \right)
\]

is obtained.
(g) Then if Eq.(18) is inserted into Eq. (14),

\[
E_{H(accumulation)} = \eta_{MP} \cdot (E_{el(PV)} - E_{el(overhead)}) + E_{H(IN)} - E_{H(looses)}
\]  \hspace{1cm} (19)

is obtained.

(h) If this Eq.(19) is inserted into Eq. (17),

\[
E_{el(HE)} = \eta_{TG} \cdot \eta_{MP} \cdot (E_{el(PV)} - E_{el(overhead)}) + \eta_{TG} \cdot (E_{H(IN)} - E_{H(looses)})
\]  \hspace{1cm} (20)

is obtained.

(i) by inserting Eq. (12) into Eq.(20), and by rearrangement, the final relation is obtained:

\[
E_{el(HE)} = \eta_{TG} \cdot \eta_{MP} \cdot \eta_c \cdot \eta_r \cdot A_e \cdot E_s + \eta_{TG} \cdot \eta_{MP} \cdot E_{el(overhead)} + \eta_{TG} \cdot (E_{H(IN)} - E_{H(looses)})
\]  \hspace{1cm} (21)

In closed system (Fig. 2), where energy losses can be disregarded, and if the Solar Hydroelectric power plant is not connected to the external electric power network, but only provides full energy independence of a local consumer and if there is no water flow in the upper reservoir 6, the

Equation is reduced to the relation:

\[
E_{el(HE)} = \eta_s \cdot \eta_{TG} \cdot \eta_{MP} \cdot \eta_c \cdot \eta_r \cdot A_e \cdot E_s
\]  \hspace{1cm} (22)

where \(\eta_s\) is efficiency of solar energy exploitation by the motor pump unit 3 and 4, which should be introduced if the energy sent to the network is disregarded (i.e. for \(E_{el(overhead)} = 0\)).

If we want to express Eq. (22) in dependency of the total electric energy produced by the PV power plant 1, the following is obtained:
In this approximation, Eq. (22) shows that electric energy $E_{ev(HE)}$, which the Solar Hydroelectric power plant produces and sends to users of the local consumer to provide power supply in a given period, directly depends on total radiated solar energy $E_{s}$ in the same period. Eq. (23) shows the dependency of the produced electric energy of the HE power plant 8 and 9 on total electric energy produced by the PV power plant 1.

D) Total head water rise

It is desirable that the net available drop of the HE power plant 8 and 9 $H_{n}$ exceeds the total head of the PV power plant 1 pumping unit 3 and 4 $H_{TE}$ ($H_{n} > H_{TE}$), providing, naturally, that local conditions allow it. It is obvious that the positive difference between the net available HE power plant 8 and 9 drop and total head of the PV pumping unit 3 and 4 $AH$ ($AH = H_{n} - H_{TE}$) most directly effects the power reduction of the PV power plant 1. Due to that, the selection of good location for water intake 10 and HE power plant 8 and 9 can lead to significant reduction of construction costs of the Solar Hydroelectric power plant, and particularly of the PV power plant 1. Naturally, this means that water discharged from the hydroelectric power plant 8 and 9 is not captured for pumping into the upper reservoir 6, but another intake, at higher level, is used for this purpose. If the same intake 10 is used, then:

$$E_{ev(PV)} > E_{ev(HE)}$$  \hspace{1cm} (24)

As the total head of water rise into the reservoir 6 $H_{TEb(i)}$ depends on water quantity $Q_{pv(i)}$ brought from the lower reservoir 10 (sea, aquifer, watercourse, etc.), water taken to the turbines 8 $Q_{G(i)}$ and volume (i.e. water level) of upper reservoir 6 $V_{i}$, the following relation can be defined:

$$H_{TEb} = f(Q_{pv(i)}, Q_{G(i)}, V_{i})$$  \hspace{1cm} (25)
which basically represents the functional constraint which can approximately be expressed as follows:

\[ H_{\text{TECO}} = \frac{H_1(V_{6}) + H_1(V_{7})}{2} - \frac{H_1(W_{6}) + H_1(W_{7})}{2} + H_p \]  

(26)

where \( H_1(V_{6}) \) and \( H_1(V_{7}) \) are upper water levels in function of upper reservoir 6 volumes respectively; \( H_1(W_{6}) \) and \( H_1(W_{7}) \) are upper water levels in function of lower reservoir 10 volumes \( W_{6} \) and \( W_{7} \) respectively, and \( H_p \) represents linear and local hydro dynamical losses in the system 5 and 7.

D). Determining the nominal electric power of the PV power plant 1

In the systematic approach to the problem of determining optimal nominal electric power of the PV power plant 1, Eq. (5) has been transformed in this work into Eq. (6), in order to show direct dependency on quantity of the pumped water. However, in order to connect and include the characteristics of other system components, Eq. (26) is inserted into Eq. (6) and instead of load matching factor \( f_m \) in Eq. (6), inverter efficiency \( \eta \) can be used, which can include the efficiency of the entire electronic system for power conditioning to the PV generator 1 characteristics. By combining this efficiency with the motor pump unit 3 and 4 efficiency \( \eta_{MP} \) into one efficiency \( \eta_{MP1} \) and by inserting it in Eq. (6), the final equation for the calculate of electric power of the PV power plant 1 is obtained:

\[ P_{el(1)} = \frac{13\alpha H_1(V_{0}) + H_1(V_{0}) - H_1(W_{0}) - H_1(W_{0}) + 2H_p}{\frac{1}{2} - \frac{\eta_{MP1}^{\text{E}}}{2} - P_{N(1)}} \]  

(27)

where all values have already been described.
In this approach, for set output water quantities \( j>v(i) \) (discretized values of decision variable), the values of nominal electric power are calculated by Eq. (27).

In this manner, through \( Q_{PV}(i) \), which represents the output water quantity from PV power plant 1 and also the input water quantity into the upper reservoir 6, water (electric energy) requirements in the periods when there isn't sufficient water in the reservoir 6 and the possibilities of their fulfilling by means of PV power plant 1 are connected.

Namely, \( Q_{py}(i) \) is by the upper reservoir 6 water balance Eq. (10) correlated to reservoir 6 characteristics, water volume \( V(i) \) and \( V_{(i-1)} \) and local climate elements (inflow \( Q_{A}(i) \) precipitation \( R(i) \), evaporation \( E_{V}(i) \) and infiltration \( INF(i) \)) that determine water deficits in the reservoir 6 which are to be covered by the PV power plant 1.

F) Mathematical model

The calculation methodology is based on dynamical programming using the complex function of minimizing the maximum electric power of the PV power plant 1.

Recursive formulas of the optimization process by dynamic programming, for the purpose of minimizing the maximum objective function, calculating in advance, because starting conditions are known, can be expressed.

In this concrete case of optimizing the nominal power of the PV power plant 1 operating together with the HE power plant 8 and 9, where state variables are expressed by water quantity in reservoir 6 \( V(i) \) in stage \( i \), i.e. \( F_{(i-1)} \) in stage \( i-1 \), and decision variables \( Q_{PV}(i) \) are expressed by mean water quantity from the PV power plant 1 in stage \( i \), recursive formulas can be expressed as follows:

\[
\begin{align*}
   f(i)(F_{(i)}) &= \text{MIN} \{ \text{MAX} \{ P_{e(i)}(Q_{PV}(i)) / (i-i)(F_{(i-1)}) \} \} . \\
   Q_{PV}(i) &
\end{align*}
\]

The relation (28) is valid in conditions of state transformation equation (10), calculation of nominal electric power \( P_{e(i)} \) by Equation (27) which represents return, and with all mentioned constraints and defined time stage \( i \), i.e.:
\[
V_C - V_{C-1} - \frac{1}{Q_{\text{PV}(i)}} - \frac{1}{Q_{\text{VCL}(i)}} - R_e - EV_{(i)} - \frac{1}{Q_{\text{OXY}}} \\
\]

\[
P_{\text{el}(i)} = \frac{134H_1(V_{(i-1)} + H_2(V_{(i)} - H_1(V_{(i-1)} - H_E(V_{(i)} - H_F(V_{(i)} - 2H_F}})}{\left[1 - \alpha_{\text{el}(i-1)} - T_0\right] P_{\text{PV}(i)}} \\
\]

\[
V_{\text{MIN}} \leq V_{(i)} \leq V_{\text{MAX}} \\
V_i = V_{\text{MIN}} = V_{\text{MAX}} \\
0 \leq Q_{\text{PV}(i)} \leq Q_{\text{MAX}} \\
i = 1, 2, \ldots, N.
\]

State variable values in observed time stages \( V_{(i)} \) and in previous time stages \( V_{(i-1)} \), and values of decision variable \( Q_{\text{PV}(i)} \), as well as returns per various stages \( P_{\text{el}(i)} \), are calculated in the course of the process. Optimal electric power of the PV power plant 1, which operates with the HE power plant 8 and 9 is obtained as the output result, providing independence of energy supply to the consumer/settlement in the observed period, i.e. throughout the whole year.

Equations (29) represent the mathematical model for optimal sizing of nominal power of the PV power plant 1 operating together with water reservoir 6.

G) Realization of the invention

For the purpose of producing a detailed description of realizing the invention of Solar Hydro Electric power plant, the model was applied to power supply of the Island of Vis in Croatia and the adjoining small islands.

The input data on electric power consumption in the period of one year (2007) were used, obtained from electrical utility Elektrodalmacija Split (annual total is 18047.48 MVAh). Total head is \( H_{\text{TE}} = \)
215 ni. Included were also data on climate, i.e. data on solar radiation $E_s$ (kW/m$^2$day), air temperature $T_a$ ($^\circ$C/day), precipitation $R$ (mm/day) and evaporation $E_V$ (mm/day). All these data were obtained from the Meteorological and Hydrological Service of Croatia for measurements from the year 1995-2006 (the data regarding precipitation is from 1981). Considering that on the Island of Vis there are no natural inflows from the adjacent watershed into the reservoir, that value was disregarded ($Q_{NAT}=0$). Due to the presumption that reservoir 6 with impermeable foils will be constructed, infiltration was also disregarded ($INF=O$).

Apart from the mentioned, important data is reservoir volume 6. For the need of full energy independence (continuous supply of a consumers throughout the whole year) the volume is determined based on peak energy consumption and the expected longest period when the PV power plant 1 is at standstill. Based on the data that the maximum (peak) water (energy) consumption from the reservoir 6 could be 166.233 m$^3$/day, with unobstructed energy supply of the consumers in the period of 3 to 4 months, total reservoir volume 6 of approximately 20,000,000 m$^3$, or 20 hm$^3$ is obtained. Therefore, the model included the reservoir 6 of average area 1500x700 m$^2$ (about 100 ha, which is important information for precipitation and evaporation estimate) and average depth of 20 m. It is a shallow reservoir 6 where level changes do not affect significantly the water surface area.

Important data is also water total head which is in the so-called pump operation (when the PV power plant 1 pumps water from the sea or groundwater 10 into the reservoir 6) about 235 m.

Therefore, in order to provide continuous power supply to the Island of Vis, the peak power of the Solar Hydro Electric power plant should be $P_{\Delta\lambda}^{\ast} = 41$ MW$_p$. For the PV power plant power of 41 MWp (41x100 kWp), with PV generator 1 efficiency of $\eta_{bc}=16\%$ in reference conditions, collector field of 250,000 m$^2$ (~25 ha) should be foreseen, i.e. approximately 1250x200 m$^2$. 
7) APPLICATION OF THE INVENTION

Solving the problem of daily and seasonal energy storage by hydro potential by this invention numerous possibilities for application of such systems are created, which could strongly encourage the PV generator 1 industry, and significantly contribute to participation of solar energy in energy balances of some countries.

Furthermore, it means that these self-sustainable systems, that would provide full energetic independence of power supply to a certain consumer, i.e. that would fully exploit the available solar energy and hydro potential at a certain location, with minimum impact on the environment, could have a safe future.

LIST OF SIGNS AND SYMBOLS

SIGNS:

1) Solar photovoltaic power plant (photovoltaic generators),
2) Inverters (transform DC into AC, includes the so-called maximum power trackers),
3) Electro motor,
4) Pump,
5) Pipeline that raises water from upper level of lower reservoir to upper reservoir,
6) Upper reservoir,
7) Pipeline that lowers water from upper reservoir to upper level of lower reservoir,
8) Turbine,
9) Generator,
10) Lower reservoir (sea, big river, aquifer etc.)
LIST OF SYMBOLS

- $\Delta \Phi_{\text{HE}}$ - net electric energy produced by HE (VAs);
- $E_{\text{el(MW)}}$ - electric energy which the PV power plant sends to the pumping unit (Ws);
- $E_{\Phi}^{\text{head}}$ - electric energy which the hydroelectric power plant sends to the power network (Ws);
- $E_{\text{el(PV)}}$ - total electric energy produced by the PV power plant (Ws);
- $E_W$ - hydraulic energy (Ws);
- $E_{\text{el,mutant,}}$ - available hydraulic energy in the network (Ws);
- $H_{\text{gross}}$ - total hydroenergy generated by reservoir (Ws);
- $E_{\text{el}(N_{\text{f}})}$ - hydraulic energy of water inflow (Ws);
- $E_{\Phi_{\text{losses}}}^3$ - hydraulic energy losses (Ws);
- $E_{\text{el,losses,accumulated}}$ - hydraulic energy losses in upper reservoir (Ws);
- $E_{st,\text{intake}}$ - hydraulic energy losses at water intake (Ws);
- $E_{i,j}$ - mean radiation on horizontal plane (terrestrial radiation) in time stage $i$ (kWh/m²);
- $E_{\text{evaporation}}$ - evaporation in time stage $i$ (mm);
- $I_m$ - load matching factor to PV generator characteristics;
- $g$ - gravity constant (9.81 m/s²);
- $h$ - height difference of upper and lower water level (m), in general;
- $H^I_{\text{diff}}$ - difference between the lower level of upper reservoir and upper level of lower reservoir (m);
- $H^I_{\text{local}}$ - linear and local hydro dynamical losses within the system (m);
- $H_{\text{upper}}$ - upper water level in lower reservoir (m);
- $H_{\text{net available drop}}$ - total head (m);
- $H_{\text{upper}}$ - upper water level (m);
- $i$ - time stage (increment);
- $I_{\text{F,}}$ - infiltration in time stage $i$ (mm);
- $N$ - total number of time stages $i$;
- $\eta_{\text{days}}$ - number of days in time stage $i$;
- $P_{\text{nom}}$ - nominal electric power of the PV generator, i.e. PV power plant in time stage $i$ (W);
- $P_{\text{el(gross)}}$ - total power of hydro accumulation (W);
- $Q$ - water flow in general (m³/s);
- $Q_{\Phi_{\text{in}}}^3$ - water inflow to intake (m³);
- $Q_{\text{Max}}$ - maximum water pumped by the motor/pump unit in given period (m³);
- $Q_{\text{Net inflow from adjacent watershed in time stage } i}$ (m³);
- $\Delta \Phi_{\text{el}}$ - water pumped by PV power plant into the upper reservoir (decision variable in time stage $i$ (m³);
- $Q_{\text{taken to the turbines in time stage } i}$ (m³);
- $R_{\text{t, precipitation in time stage } i}$ (mm);
- $T_{\text{ref}}$ - referential temperature of PV cell (generator) (25 °C);
- $T_{\text{env}}$ - temperature of the surroundings in time stage $i$ (°C);
- $V_{\text{total water losses in upper reservoir}}$ (m³);
- $V_{\text{intake}}$ - water losses at intake (m³);
- $V_{\text{flow into upper reservoir}}$ (m³);
- $V_{\text{accumulated}}$ - losses in upper reservoir (m³);
- $F_{\text{water flow into upper reservoir}}$ (m³);
- $V_{\text{flow out from upper reservoir}}$ (m³);
- $W_{\text{Stage}}$ - lower reservoir volume in time stage $i$ (m³);
- $\alpha_{\text{PV}}$ - PV cell (generator) temperature coefficient (°C⁻¹);
- $\eta_{\text{el}}$ - hydroelectric power plant efficiency (%);
- $\eta_{\text{in}}$ - inverter efficiency (%);
- $r_{\text{MPU}}$ - motor-pump unit efficiency (%);
- $\eta_{\text{acc}}$ - efficiency of motor-pump unit and inverter (%);
- $\eta_{\text{el,PU}}$ - nominal efficiency of PV generator (%);
- $\eta_{\text{el,PU}}$ - efficiency of solar energy exploitation by the pumping unit (%);
- $H_{\text{GT}}$ - total efficiency of turbine and generator assembly (%);
- $p$ - water density (1000 kg/m³).
8) PATENT REQUIREMENTS

1) Solar Hydro Electric power plant, characterized by photovoltaic generator (1), inverter (T), electro motor (3), pump (4), one or more water reservoirs (6 and 10), pipeline (5) for pumping water from lower reservoir (10) into upper reservoir (6), pipeline (7) that conveys water from upper reservoir (6) into lower reservoir (10), turbines (8) and generator (9).

2) Solar Hydro Electric power plant, compliant to Requirement 1. characterized by continuous supply of electric energy to a consumer.

3) Solar Hydro Electric power plant, compliant to Requirements 1 and 2, characterized by open upper (6) and lower (10) reservoir, represents the so-called open type of Solar Hydro Electric power plant.

4) Solar Hydro Electric power plant, compliant to Requirements 1 and 2, characterized by closed upper (6) and lower (10) reservoir, represents the so-called closed type of Solar Hydro Electric power plant.

5) Solar Hydro Electric power plant, compliant to Requirements 1 and 2, characterized by one open (6 or 10), and one closed (6 or 10) reservoir, represents the so-called combined type of Solar Hydro Electric power plant.

6) Solar Hydro Electric power plant, compliant to Requirements 1-5, characterized by the size of the PV generator (1) determined based on the presented mathematical model.
A. CLASSIFICATION OF SUBJECT MATTER
INV. F03B17/00 F03G6/00 E04H5/02 F01K27/00 H02B7/00
According to International Patent Classification (IPC) or to both national classification and IPC.

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
F03B  F03G  E04H  F01K  H02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>DE 197 20 700 A1 (HOEFFKEN ARNO [DE]) 19 November 1998 (1998-11-19) the whole document</td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>WO 2004/004816 A (ASSAD ASSAD BESHARA [EG]) 4 November 2004 (2004-11-04) the whole document</td>
<td>1</td>
</tr>
<tr>
<td>Category</td>
<td>Citation of document, with indication, where appropriate, of the relevant passages</td>
<td>Relevant to claim No</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>A</td>
<td>DE 100 01 618 A1 (MEULEMAN ANDRE [DE]) 19 July 2001 (2001-07-19) the whole document</td>
<td>1</td>
</tr>
<tr>
<td>Patent document cited in search report</td>
<td>Publication date</td>
<td>Patent family member(s)</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-----------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>DE 10123240 A1</td>
<td>14-11-2002</td>
<td>NONE</td>
</tr>
<tr>
<td>DE 19720700 A1</td>
<td>19-11-1998</td>
<td>NONE</td>
</tr>
<tr>
<td>WO 2004094816 A04</td>
<td>04-11-2004</td>
<td>NONE</td>
</tr>
<tr>
<td>DE 10001618 A1</td>
<td>19-07-2001</td>
<td>NONE</td>
</tr>
</tbody>
</table>