A HYBRID COOLING SYSTEM FOR GEOTHERMAL PLANTS BASED ON GROUNDWATER COOLING: FIRST SIMULATION RESULTS AND TECHNICAL FEASIBILITY

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ABSTRACT

The conversion efficiency of low-enthalpy geothermal binary plants is very sensitive to the condensing temperature of the prime mover, which in turn depends on the ambient temperature. In a combined heat and power (CHP) installation, the impact on electricity production of weather conditions is somehow amplified: the electric output of the plant is maximum during summer since the heat demand reaches its minimum, but the ambient temperature is higher, thus limiting the plant conversion efficiency. On the other hand, the optimal weather conditions for electricity generation occur during winter, when the prime mover thermal input is generally minimal due to the higher heat demand.

Three types of cooling system are traditionally adopted in geothermal power plants: 1) air cooled condensers 2) direct water cooling or 3) mechanical-draft cooling towers. ACC and WCT are the most common solutions. To reduce the impact of high ambient temperatures on the performance of binary CHP plants and at the same time limit the water consumption, a new hybrid cooling system is proposed in this paper, which exploits a shallow aquifer as cold thermal energy storage. The advantages are: 1) the use of groundwater is generally more economical than the use of non-saline surface water; 2) groundwater has an almost constant temperature over the seasons, and 3) it can be used in a closed loop, thereby avoiding the consumption of this important natural resource.

The proposed hybrid cooling system is being the subject of extensive numerical simulations by VITO in the framework of the European project Matching. The results described in this paper indicate as optimal strategy the use of groundwater only in the case of high ambient temperatures. Moreover, during cold periods, the groundwater used to cool down the binary plant has to be re-extracted, cooled in the dry cooler and reinjected at a temperature close to that of the original aquifer in order to prevent a thermal pollution of the aquifer. The benefit quantified in this paper is an increase in the plant electricity production of about 4%, without any water consumption and at the cost of a limited temperature anomaly in the wells field. However, this gain seems, to a first analysis, insufficient to pay back the investment costs for the implementation of the hybrid cooling system.

1. INTRODUCTION

The technology currently most suitable for the conversion into electricity of low-temperature liquid-dominated geothermal sources is that based on the Organic Rankine Cycle (ORC) concept: the prime mover of the plant adopts a phase-changing organic compound as evolving fluid to implement the working principle defining the Rankine cycle. The conversion efficiency of an ORC power plant, often called binary plant in the geothermal field is, however, bound to be low, in the order of 10% or less for low-temperature sources (100 – 150 ºC) (DiPippo, 2012). It results, then, that the sole electricity production does not ensure the economic profitability of the geothermal project, given the generally high cost of drilling and construction of the brine wells. A possible solution to ensure the profitability consists in designing the binary plant for combined heat and power (CHP) generation: part of the geothermal energy is used to supply thermal energy to district heating networks, thus enabling a significantly higher utilization of the heat source driving the conversion process. Examples of such a geothermal power plant concept are the plant of Neustadt (Menzel, 2000) in Germany or the CHP stations of Altheim (Pernecker, 2002) or Bad Blumau in Austria (Legmann, 2003). The brine wellhead temperature in these power plants is as low as 100 ºC. According to the European Geothermal Energy Council (EGEC), other CHP binary plants are currently under development in Europe, especially in Germany, France and Hungary. Among these, there is also the Balmatt plant in Belgium, which is under construction by the research institute VITO. VITO's goal is to demonstrate the economic feasibility of CHP deep geothermal power plants exploiting the low-enthalpy reservoirs typical of Campine region in Belgium (Bos, 2018).

Another key element of low-enthalpy geothermal plants is the cooling system. The ORC unit performance is, indeed, very sensitive to the condensing temperature of the working fluid, which in turn depends on the ambient conditions and the chosen cooling solution. Three types of cooling system are traditionally adopted in geothermal power plants: 1) air cooled condensers (ACC) 2) direct water cooling (DWC) or 3) mechanical-draft cooling towers (CT). ACC and WCT are the most common solutions (DiPippo, 2012), since the use of large amounts of surface water, if available, is, nowadays, usually prohibited by environmental agencies to prevent the thermal pollution of the natural environment.

The key advantage of the use of ACC is that no water is consumed, but the auxiliary power consumption of the cooling system might be two or three times higher than in the case with WCT. Similarly, the investment cost of a binary plant with ACC can be 50% higher than that of a similar plant equipped with WCT, especially if low condensing temperatures are targeted in the design. Besides, the ACC performance is more affected by hot weather conditions. For these reasons, the year-round net electricity output of a low-enthalpy geothermal power plant with a WCT tends to be higher than that of a plant with the same thermal source but adopting ACC. The difference can be up to 30-40% (Walraven, 2015). In a CHP installation connected with a district heating network, the gap in electricity production is expected to increase, since the impact on electricity production of weather conditions is somehow amplified: the electric output of the plant is maximum during summer because the heat demand reaches its minimum, but the higher ambient temperature limits the plant conversion efficiency. The optimal weather conditions for electricity generation occur during winter, when the brine mass flow rate fed to the ORC unit is, however, reduced to supply thermal energy to the district heating network.

On the other hand, WCT-based systems have the high water consumption as drawback. This is becoming a critical aspect for power plants in Europe. According to the European Environmental Agency (EEA, 2010), in 2010, cooling water for energy production accounted for 45% of the total fresh water abstraction in the European Union. The use of surface water for cooling purposes in Europe is, then, expected to become more and more restricted in the upcoming years, due to the current overabstraction of freshwater, and the increasingly dry weather of the continent.

An ideal cooling system for CHP binary plants should, then, feature no water consumption, like in the case of air cooling, together with a strong performance resilience to high ambient temperatures. To this purpose, VITO is studying a novel hybrid cooling system which exploits a shallow aquifer as ATES (Aquifer Thermal Energy Storage) to cool down the ORC plant condenser in the case of hot weather conditions. Since the shallow aquifer has an almost constant temperature over the seasons, the cooling system performance is potentially unaffected by the rise in ambient temperature during summer. At the same time, the groundwater is used in a closed loop. Thus, no water is consumed.

The proposed hybrid cooling (HC) system is being the subject of an extensive feasibility study carried out by VITO in the framework of the European project MATChING. This paper documents part of this work, focusing on the assessment of the electricity production gain achievable by means of the HC system in a low-enthalpy geothermal application.

2. THE TEST CASE

The geothermal site of Balmatt in Belgium was considered as test case of the feasibility study. This is due to the availability in this location of a shallow water aquifer with characteristics suitable for the implementation of the proposed groundwater-based cooling system. The results of the study are, however, applicable to any low-enthalpy geothermal power plant, provided that a sufficiently thick and highly permeable aquifer is present in the proximity of that plant.

The Balmatt plant is situated in the Belgian Campine region near the city of Mol. The geothermal reservoir is at a depth of about 3300 m bgl and features a brine temperature around 128 °C. Two wells have been so far completed, but when operating at its full potential, the plant should consist of 5 wells for a total expected supply of 194 kg/s of brine. The thermal energy of the brine will be used to supply heat to a district heating network or to power an ORC system to produce electricity. Due to the corrosiveness of the brine, an intermediate water loop is built between the geothermal source and the ORC unit or the district heating network. Consequently, the actual maximum temperature of the thermal source of the plant is lowered to 120 °C. The primary heat exchanger of the ORC system and the heat exchanger of the DH are fed with hot brine at the same temperature. This layout is defined “parallel” configuration and it is generally the optimal solution when the geothermal source is of the low-enthalpy type and the supply temperature of the district heating network is relatively high (Van Erdeweghe, 2017), e.g. 90°C, as for the Balmatt plant.

The local shallow aquifer which can be exploited for the implementation of the HC system is, instead, characterized by a thickness of ca. 115 m, a permeability of 10 m/day, a natural hydraulic gradient of 0.001 m/m and a mean water temperature of 11 °C.

3. THE CONCEPT

The conceptual layout of the HC system under study is shown in Figure 1. The groundwater cooling loop consists of multiple extraction wells in parallel, hereafter named cold wells, which are connected to the cooling loop of the ORC plant and then to the reinjection wells, called the hot wells. A pair of extraction and reinjection wells connected together is called doublet. Water is extracted from the shallow aquifer (cold wells) when hot weather conditions occur to cool down the ORC unit in place of the air coolers of the plant (**Cooling Mode 1**). After being used in the ORC condenser, the groundwater is injected back into the aquifer (hot wells) at about 25 ºC. Higher injection temperatures are generally not allowed to prevent alteration of the water quality in the aquifer. The maximum reinjection temperature differs across the European countries, but it is generally between 20 - 25 ºC. In Belgium, the limit set by the legislator is 25 ºC.

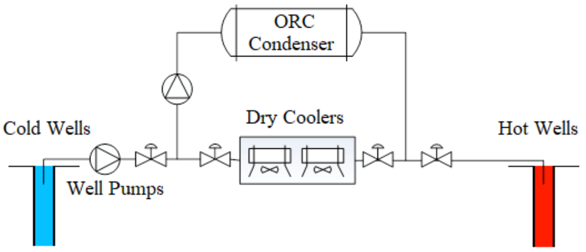

Figure 1: Conceptual layout of the hybrid cooling system.

Since the maximum thermal load in the condenser is about 42 MW for the plant of the case study, it results that extraction wells must supply 725 kg/s of groundwater to cool down the ORC unit when this is at full capacity. Considering, then, that the typical capacity of a groundwater well is between 100 - 150 m3/h (~ 20 – 42 kg/s), the number of doublets needed to implement the proposed HC system ranges for the Balmatt plant from 18 to 26.

When the ambient temperature is low, indicatively below 15 ºC, the use of groundwater is not favourable. The ORC unit is, then, cooled down by means of air coolers (**Cooling Mode 2**) and the cooling water is circulated in closed loop. The condensing temperature of the binary plant becomes a function of the coolers performance, which, in turn, depends on the fan speed set-point and the ambient temperature.

Moreover, to reduce the extension of the thermal anomaly in the aquifer and to guarantee a sustainable exploitation of this resource, the warm groundwater stored in the hot wells is cooled down during winter to the original temperature of 11 ºC. Warm water from the hot wells is, then, re-extracted, fed to the air coolers of the plant and then reinjected into the cold wells (**Cooling Mode 3**). The flow direction from the cold wells to the hot wells is, thus, reversible. This is achieved by a system of valves and piping which is not shown in Figure 1. Note that the cooling of the warm groundwater can be performed by using the same dry coolers of the ORC unit, since, in case of cold weather conditions, the heat demand of the district heating network is high. Given the adopted plant configuration, it results that the thermal load of the ORC unit is low. During the coldest day, it can even happen that the brine flow rate available for electricity production is not enough for the operation of the ORC turbo-generator.

4. THE METHOD

The assessment of the proposed HC system required i) the development of an off-design model of the binary plant, so as to evaluate its performance under different operating conditions (e.g. ambient temperatures, heat demand of the heating network, air coolers fan speed, groundwater mass flow rate extracted etc.), and ii) the implementation of an ad-hoc optimization algorithm to identify the optimal operating policy. This establishes when the HC system should be operated in mode 1, 2 or 3, depending on the ambient temperature, the heat demand of the network, and the amount of warm stored in the hot wells. These two activities are described in the following.

4.1 THE SYSTEM MODEL

The off-design model of the binary plant has been developed in the modelling language Modelica (Mattsson, 1997), following an objected oriented modelling approach: first, dedicated off-design models for the air coolers and each of the components of the ORC unit are implemented. The individual component models are, then, combined together to build the system model of the plant. Regarding the characteristics of the component models, the heat transfer equipment is modelled by adopting the well-known ε-NTU method (Incropera, 2007), where the variation of the heat transfer as a function of the hot and cold stream mass flow rate is accounted with simplified correlations. The turbine performance is, instead, predicted by using empirical correlations for the isentropic efficiency and mass flow coefficient, which have been calibrated based on the results of a quasi-1D model of the turbine.

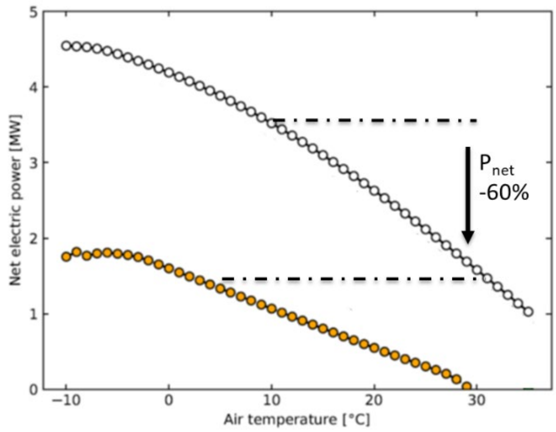

Figure 2: ORC net power versus ambient temperature. White dotted line: ORC at full load (not heat demand); Orange dotted line: 50% of maximum heat demand of the heating network.

Figure 2 shows the variation in the net power production of the ORC unit predicted by the off-design model for two plant loads as a function of the ambient temperature. In particular, the white dotted line is representative of typical operating conditions during summer, namely when there is no heat demand from the heating network, while the orange line corresponds to operating conditions typical of winter. The drop in net electricity production during summer can be as high as 60%, if compared to the case when the air temperature is 11ºC, i.e. approximately the average ambient temperature in Belgium. The net power of the plant when air temperature is about 30ºC can be even lower than that of the plant during winter time. The cooling of the ORC unit by means of groundwater should mitigate the penalty in electricity production caused by hot weather conditions.

4.2 THE OPTIMIZATION ALGORITHM

The optimal operating policy for the HC system is that maximizing the electricity production of the plant and guaranteeing at the same time that the groundwater injected during summer in the hot wells is extracted in winter and cooled down to the original aquifer temperature. This problem can be formulated as an equivalent optimal control problem with a time horizon of one year, a final constraint that forces all valid solutions to have

$$V_{water\ injected} = V_{water\ extracted} \qquad [1],$$

and an objective function equal to the total net electricity generated by the plant over the considered time horizon:

$$\sum E_{el}(t) = \sum\left(P_{turbine} - P_{pump,ORC} - P_{pump\ cool.loop} - P_{wells\ pumps} - P_{air\ coolers}\right) \cdot 1\ hr \qquad [2].$$

The state of the system is, instead, represented by the temperature distribution in the aquifer. This is predicted by a simplified model obtained by discretizing the portion of shallow aquifer around the hot wells in a sequence of cells connected in series and located at an increasing distance from the wells borehole. In each cell, mass and energy balance equations are solved assuming an uniform porosity of the aquifer.

The equivalent optimal control problem above is tackled by an *ad-hoc* optimization algorithm, specifically devised for this application. First of all, to reduce the computational burden of the problem, the optimizer can choose at each time step only among a limited set of discrete actions. These are:

1. Action 1: the ORC unit is cooled by the dry coolers only, and no groundwater is extracted from the hot wells.
2. Action 2: groundwater from the cold wells is extracted at maximum rate (42 kg/s) to cool down the condenser of the ORC unit. This action is enabled only if the ambient temperature is ≥ 15 °C.
3. Action 3: groundwater is extracted at the maximum allowed rate from the hot wells, it is cooled down to 11 °C and it is injected back into the cold wells. The maximum groundwater mass flow rate that can be extracted from the hot wells depends on whether the ORC unit is in operation or not, since this is also cooled via the air coolers. Groundwater extraction from the hot wells is considered only when the air temperature is ≤ 8 °C.

The optimization method is based on an approximate merit order ranking technique. Figure 3 shows the main conceptual steps or the pseudo-code of the policy search algorithm. First, for each hour of the year where T_{air} ≥ 15 °C, the merit associated with the use of cold groundwater in the ORC condenser is determined, see line 2 in Figure 3. The merit *M* is equal to the increase in electricity production achievable by using water cooling in place of air cooling, divided by the corresponding thermal energy injected in the hot wells. Notice that the value of *M* at time t does not depend on the hot well state and can, therefore, be calculated upfront based on the ambient temperature and the heat demand of the heating network at that time. The cost *C* associated with water extraction from the hot wells (see line 3.2 in Figure 3) is, instead, the electricity consumption of the air coolers required to cool down the extracted groundwater to 11 ºC, divided by the corresponding thermal energy removed from the hot wells. *C* depends, then, on the hot wells state, represented by the temperature distribution in the aquifer.

```
1. Set iteration limit
2. Find merit order M for all possible injection hours (Tair >= 15 °C)
3. Set N == maximum number of feasible extraction hours (Tair <= 8 °C)
4. For it iterations:
   4.1.  Select >=1000 random sets of N extraction hours
   4.2.  Calculate the average cost C(it)associated with each extraction
         hour
   4.3.  Sort C(it), lowest cost first.
   4.4.  Build the combined merit order M - C(it)
   4.5.  The combination of injection hours and extraction hours where M -
         C(it) is positive constitutes the policy(it)
   4.6.  Calculate the results of the above policy
   4.7.  Update the value of N according to the number of extraction hours
         identified at point 4.6 and repeat step 4.2 - 4.7
   4.8.  Stop iteration when no improvement or iteration limit id reached
5. Select the policy(it) with the best result.
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Figure 3: Pseudo-code of the policy iteration algorithm using Merit Order Approximation.

5. RESULTS

Figure 4 summarizes the main results of the optimization. The red line in the top graph represents the cumulative curve of the electricity production of the plant when groundwater is used to cool down the ORC unit and the constraint on the total volume of groundwater injected in the hot wells is not applied (unconstrained case). The blue line, instead, indicates the case where the groundwater injected during summer in the hot wells is extracted in winter and cooled down to the original aquifer temperature (constrained case). The black curve is the baseline case, where the ORC unit is cooled by means of the plant air coolers all over the year. In the unconstrained case, the increase in net electricity generated by the plant compared to the baseline case is almost 14%, while the gain reduces to only 4% for the constrained case.

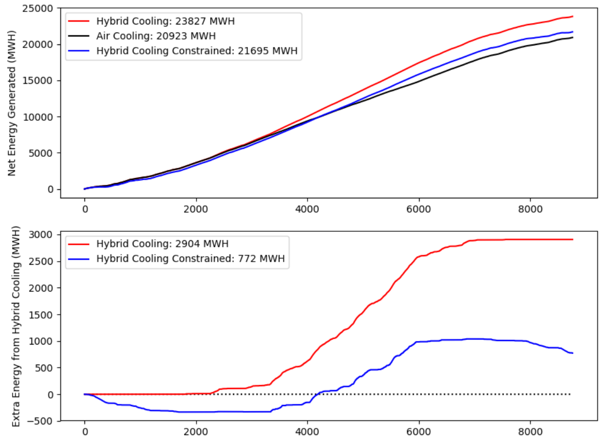

Figure 4: cumulative electricity generated by the plant (top graph) for i) the baseline case (black line), ii) the case of groundwater cooling without any constraint on water injection (red line), and iii) the case where the constraint in eq. 1 is applied (blue line). The bottom graph shows the corresponding gain in electricity production.

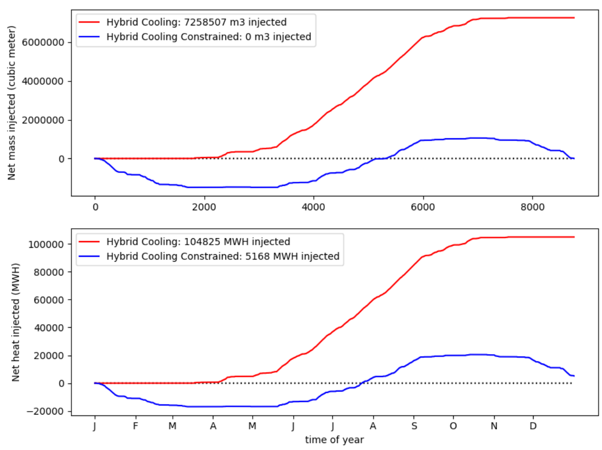

Figure 5: Groundwater injection and extraction from the hot wells during the year (top graph) and corresponding amount of thermal energy stored in the aquifer (bottom graph). Red line: no constraint on groundwater injection; blue line: constrained case.

The effect on plant operation of the constraint on the total volume of groundwater injected in the hot wells is apparent in Figure 5 (blue line). First, in winter, electricity is consumed to cool down the groundwater in the hot wells. Then, in summer, groundwater from the cold wells is used to cool down the ORC unit, thus increasing the plant efficiency. The bottom graph reports, instead, the evolution of the cumulative thermal energy injected into the hot wells over the year. Note that the extraction of a volume of groundwater equal to that injected during summer is not enough to completely remove the thermal energy stored into the hot wells. The reason is the thermal capacity of the aquifer sandstones which stores part of the thermal energy of the injected groundwater, thus cooling the latter down. The corresponding thermal anomaly in the aquifer is, however, limited, as shown in Figure 5, where the area between the black line, which is the initial temperature distribution assumed in the hot wells aquifer, and the green and red lines is proportional to the thermal energy stored in the hot wells after one year of plant operation.

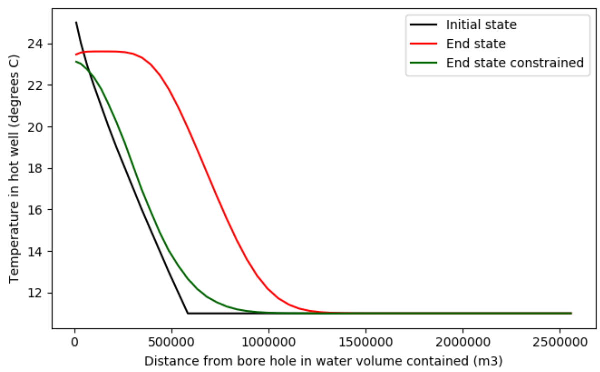

Figure 6: Hot wells temperature distribution. Black line: initial state; red line: final state of the aquifer when the constraint on the amount of water injected in the hot wells is not applied; blue line: final state in the constrained scenario.

It results that for the constrained case (green line) the thermal energy remaining in the hot wells is only a small fraction of that in the unconstrained scenario. It is envisaged that a temperature distribution equal to that of the initial state can be reached with a further, but limited, groundwater extraction. Regardless of this, the gain in electricity production for the constrained scenario is, at first glance, not sufficient to make the proposed HC system economically feasible. Assuming, indeed, a market price for electricity of 60 €/MWh, the capital expenditure (CAPEX) for the realization of the ATES system (18 doublets) should not exceed 450.000 € to guarantee a pay-back time of about 10 years. If the power plant electricity production is for own consumption, the limit value for CAPEX increases to 900.000 €, since the cost of electricity for an industrial user can be twice as much the market price. However, also in this case, the economic feasibility of the proposed HC system is not reached, being the CAPEX reported in the literature for groundwater doublets with a capacity of 120-180 m^3/hr in the order of 250.000 – 280.000 € per doublet (Jaume, 2017). Based on this specific cost estimate, profitability would barely be achieved in the unconstrained scenario, although economy-of-scale effects may be relevant when multiple doublets are drilled in the same concession area.

3. CONCLUSIONS

The hybrid cooling system assessed in this work exploits a shallow aquifer as medium to store cold energy. More in detail, the cooling system integrates dry coolers and a groundwater closed loop. Groundwater is used in place of dry coolers, when hot weather conditions occur, to mitigate the reduction in the net power production of the plant which would be caused by the ambient temperature rise. Over a year period, the groundwater used for cooling and temporarily stored in the hot wells is re-extracted, cooled down to the original aquifer temperature by means of air coolers, and reinjected in the cold wells. The aim is to preserve the original temperature of the aquifer over the plant lifetime, thus allowing for sustainable exploitation of this resource.

To assess the feasibility and advantages of the proposed cooling system and to investigate its performance under different operating conditions, a dedicated simulation and optimization tool has been developed. The analysis of the simulation results led to the following conclusions:

1. The yearly potential gain in electricity production for a CHP low-enthalpy geothermal plant achievable by using groundwater as heat sink in place of air coolers is about 14%.

2. If the volume of water injected during summer is compensated by an equal extraction of water during the cold periods of the year, the gain in electricity production reduces to 4%. This is due to the pumps electricity consumption to extract the groundwater and to reinject it back into the cold wells, as well as the air coolers consumption to cool down the water to the original temperature of the aquifer.

3. The economic feasibility of the proposed HC system may be reached only if the power plant production is for own consumption and the increase in electricity generation is in the order of 15%-20% with respect to the baseline case where dry coolers are used throughout the year. The realization of an ATES system of large capacity, such as that studied in this paper, may, however, benefit of economies of scale.

Future work will focus on the refinement of the adopted optimization algorithm (more actions, improvement of the merit order curve estimation method) and the assessment of the hybrid cooling system for climates where the seasonal variation of the ambient temperature is more prominent than in Belgium.

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