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Energy return on energy invested for the production of methane from hydrates by electrical heating and by hot water injection

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Abstract: In this paper we expand our previous publications on the energy balance (EROI) in the production of methane from methane hydrate (MH) submarine reservoirs via electrical heating and by hot water injection. In the case of hot water injection the heat transfer problem with phase change was initially solved by a standard finite difference scheme in cylindrical coordinates. Due to the low value of the thermal diffusivity of water $(\kappa_w \approx 10^{-7}\ \mathrm{m}^2/\mathrm{sec})$ this scheme proved to be unstable in the region inside the pipe located at the center of the reservoir. In the present paper, in order to avoid the numerical instability, we transform the initial finite difference scheme using the Gauss theorem. The transformed discretized system is stable. The results indicate that for a 500 meter long reservoir (with a radius of 20 meters), the flow of water in a 1 meter diameter pipe located at the center of the reservoir (initial temperature of 200 C, end temperature of 2 C, and water velocity of 1m/sec) will melt the hydrates with an EROI (energy out/energy in) of the order of 30 at the beginning of the operation, and of the order of 7 after 30 years of operation. The melting temperature considered is 20 C, corresponding to the phase diagram of methane hydrates at depths of some 1000 m.

Keywords: methane hydrates, EROI, electrical heating, hot water heating

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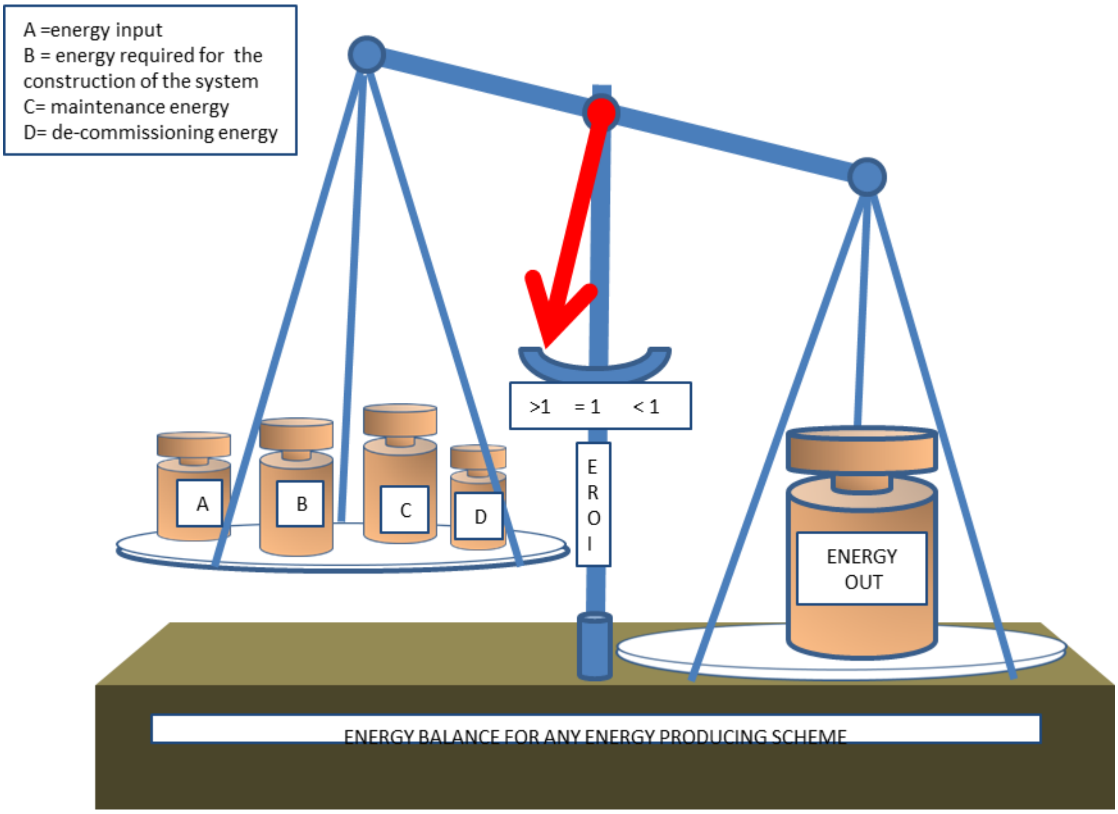
1. Introduction

In view of the large energy reserves associated with methane hydrate deposits in the word [1-3], we decided to evaluate the energy balance (energy out / energy in) associated to the possible production of methane from submarine hydrate deposits. Should this partial energy balance turn out to be less than unity, the complete EROI (Energy Return On energy Invested) would be even less than unity when the energy required for the construction, maintenance (and decommissioning) of the system is added. No additional calculation would then be required. The concept of EROI is shown in Figure 1. Figure 2 illustrates the concept of a partial EROI less than unity, where the balance of energy only considers applied energy. In the present paper we show that the partial EROI for methane hydrate production by injection of hot water is greater than 1.

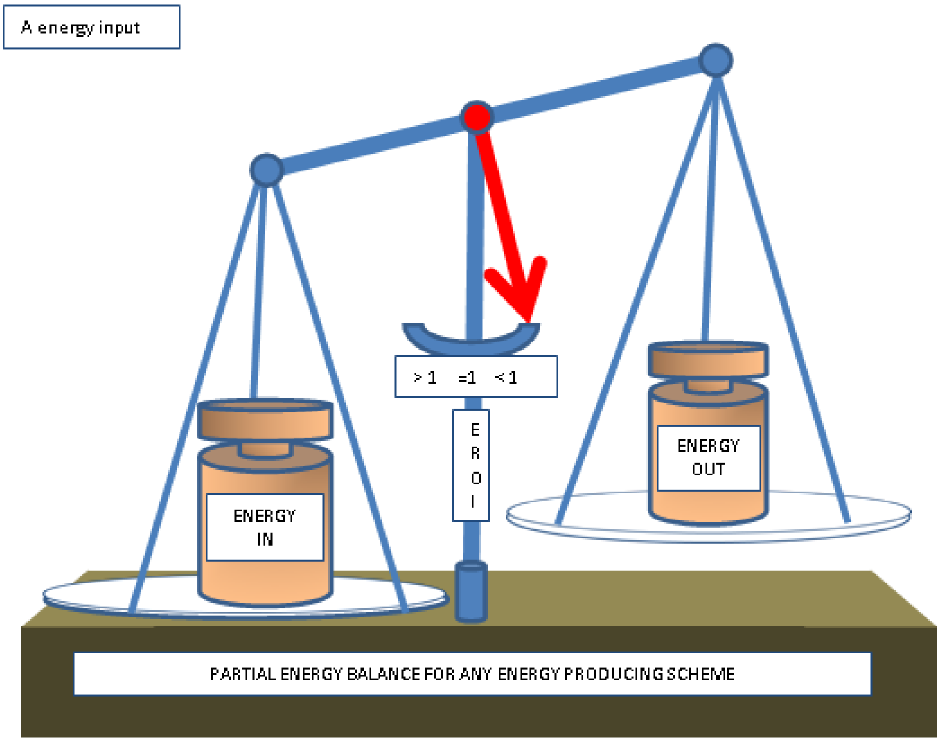
In previous related papers we discussed the electromagnetic heating of petroleum [4], and we calculated the primary energy balance (energy out / applied energy) for the possible production of methane from submarine deposits by low frequency (60Hz) electrical energy [5-6]. We examined different heater locations and different heater lengths, and found that for the optimal heater positions and lengths the EROI was 1.66

Figure 1. The concept of an EROI>1 where the produced energy is greater than the sum of the energy required for the construction of the system, plus the energy required for maintenance, plus the energy applied to the system, plus the energy required for the eventual decommissioning of the system.



If a partial balance where we do not consider construction, maintenance and decommissioning required energies, turns out to be less than one then the process will not be a valid energy producing scheme.

Figure 2.. The concept of partial EROI < 1. Only the ratio of applied energy to the produced energy is considered. If this ratio is less than one – as shown – then no further calculations are required. The process considered is NOT a net energy producer.



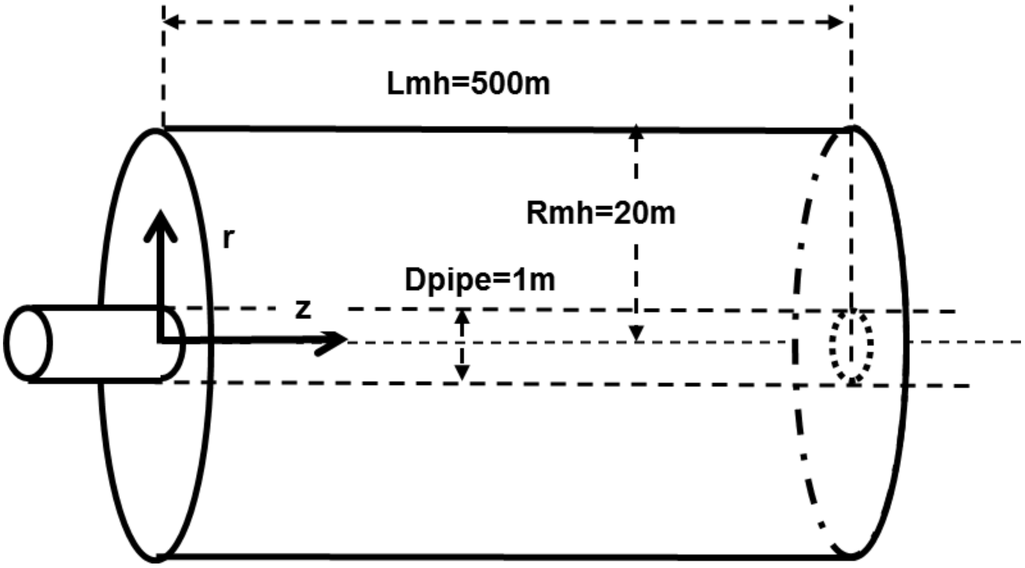
We next considered [7] the methane production via hot water injection – the scheme suggested in Japan for production in the Nankay trough [8]. We considered a methane hydrate reservoir 500 meters long with a radius of 100 meters at an initial temperature of 2 C. A pipe located at the center of the reservoir carries the hot water output of a floating cogeneration plant at 200 C [9]. The configuration of the system considered in our model is shown on Figure 3.

In order to solve this problem we first modeled the heating via a standard second order finite difference heat transfer scheme in cylindrical coordinates. The region inside the pipe considered heat conduction and convection processes, while the solution inside the reservoir considered heat conduction and change of phase of this variable boundary heat transfer problem [10], according to the enthalpy method [11]. The heat transfer equations that define the temperatures in the well Tw(r,z), and in the reservoir T(r,z), are shown below. In the well:

$$\frac{\partial^2 T_w(r,z)}{\partial r^2}+\frac{1}{r}\frac{\partial T_w(r,z)}{\partial r}+\frac{\partial^2 T_w(r,z)}{\partial z^2}-\frac{v(r)}{\kappa_w}\frac{\partial T_w(r,z)}{\partial z}=\frac{1}{\kappa_w}\frac{\partial T_w(r,z)}{\partial t} \qquad (1)$$

Where κ_w is the thermal diffusivity of water and v(r) is the velocity in the well in the +z direction.

Figure 3. The system considered: Methane hydrate reservoir: length=500m, radius=20m. Pipe: length=500 m, diameter=1m, water enters at 200 C and exits at 2 C Water velocity=1m/sec. Methane hydrate melting temperature=20 C.



In the reservoir, for temperatures below melting, the pertinent equation for the hydrate region is:

$$\frac{\partial^2 T(r,z)}{\partial r^2}+\frac{1}{r}\frac{\partial T(r,z)}{\partial r}+\frac{\partial^2 T(r,z)}{\partial z^2}=\frac{1}{\kappa_{mh}}\frac{\partial T(r,z)}{\partial t} \qquad (2)$$

Where κ_{mh} is the thermal diffusivity of the methane hydrate and (r,z) correspond to coordinates for a point where $T(r,z)\leq T_0$, temperature less than or equal to the hydrate melting temperature T_0 which we take as 20C for the depths considered of 1000 m. If we are in a zone where the temperature is greater than the hydrate melting temperature then the pertinent reservoir equation is:

$$\frac{\partial^2 T(r,z)}{\partial r^2}+\frac{1}{r}\frac{\partial T(r,z)}{\partial r}+\frac{\partial^2 T(r,z)}{\partial z^2}=\frac{1}{\kappa_{w}}\frac{\partial T(r,z)}{\partial t} \qquad (3)$$

As we described in great detail before [5-6], equation 3 is solved using the enthalpy method. At the surface pipe-reservoir the temperature continuity is obtained by applying the following boundary condition:

$$T_w(r_w,z)=T(r_w,z) \qquad (4)$$

When the volume considered is discretized ($\Delta r,\Delta z$) the finite difference expression for equation 1 becomes:

$$\frac{T^{\,k}_{wi+1,j}-2T^{\,k}_{wi,j}+T^{\,k}_{wi-1,j}}{(\Delta r)^2}+\frac{T^{\,k}_{wi+1,j}-T^{\,k}_{wi,j}}{i(\Delta r)^2}+\frac{T^{\,k}_{wi,j+1}-2T^{\,k}_{wi,j}+T^{\,k}_{wi,j-1}}{(\Delta z)^2}-\frac{v(i\Delta r)}{\kappa_w}\frac{T^{\,k}_{wi,j+1}-T^{\,k}_{wi,j}}{\Delta z}=\frac{1}{\kappa_w}\frac{T^{\,k+1}_{wi,j}-T^{\,k}_{wi,j}}{\Delta t} \qquad (5)$$

This scheme proved to be numerically unstable as the velocity value inside the pipe is increased to values above 0.002 m/sec. In reference [7] we described approximate finite difference solutions which – as expected- showed EROI values that decrease with time as the reservoir is gradually heated and all the methane produced. The produced energy will tend to a constant value when all the methane hydrates are melted.

In the present paper we present results for the complete heat exchange problem for applied hot water, where the heat transfer is determined by solving the correct discretized equations, both inside and outside the pipe, by application of Gauss theorem. This approach stabilizes the numerical procedure in the regions inside and outside the pipe, allowing stable numerical solutions.

2. Gauss theorem applied to the heat transfer equations

In order to illustrate our procedure we rewrite equations 1 and 2 in order to show their general form which involves the nabla squared operator [12]:

$$\vec{\nabla}^2 T_w(r,z,t) - \frac{1}{\kappa_w} v_z(r) \frac{\partial T_w(r,z,t)}{\partial z} = \frac{1}{\kappa_w} \frac{\partial T_w(r,z,t)}{\partial t} \tag{6}$$

$$\vec{\nabla}^2 T(r,z,t) = \frac{1}{\kappa} \frac{\partial T(r,z,t)}{\partial t} \tag{7}$$

These can be expressed as:

$$\vec{\nabla} \cdot \left[\vec{\nabla} T_w(r,z,t) - \vec{i}_z \frac{1}{\kappa_w} v_z(r) T_w(r,z,t) \right] = \frac{1}{\kappa_w} \frac{\partial T_w(r,z,t)}{\partial t} \tag{8}$$

$$\vec{\nabla} \cdot \left[\vec{\nabla} T(r,z,t) \right] = \frac{1}{\kappa} \frac{\partial T(r,z,t)}{\partial t} \tag{9}$$

We integrate over one element of volume in each region:

$$\int_{\text{volume}} \vec{\nabla} \cdot \left[\vec{\nabla} T_w(r,z,t) - \vec{i}_z \frac{1}{\kappa_w} v_z(r) T_w(r,z,t) \right] dv = \int_{\text{volume}} \frac{1}{\kappa_w} \frac{\partial T_w(r,z,t)}{\partial t} dv \tag{10}$$

$$\int_{\text{volume}} \vec{\nabla} \cdot \left[\vec{\nabla} T(r,z,t) \right] dv = \int_{\text{volume}} \frac{1}{\kappa} \frac{\partial T(r,z,t)}{\partial t} dv \tag{11}$$

We then apply Gauss theorem converting the volume integrals of the divergence of a vector to the surface integral of that vector:

$$\int_{\text{surface}} \left[\vec{\nabla} T_w(r,z,t) - \vec{i}_z \frac{1}{\kappa_w} v_z(r) T_w(r,z,t) \right] \cdot d\vec{A} = \int_{\text{volume}} \frac{1}{\kappa_w} \frac{\partial T_w(r,z,t)}{\partial t} dv \tag{12}$$

$$\int_{\text{surface}} \left[\vec{\nabla} T(r,z,t) \right] \cdot d\vec{A} = \int_{\text{volume}} \frac{1}{\kappa} \frac{\partial T(r,z,t)}{\partial t} dv \tag{13}$$

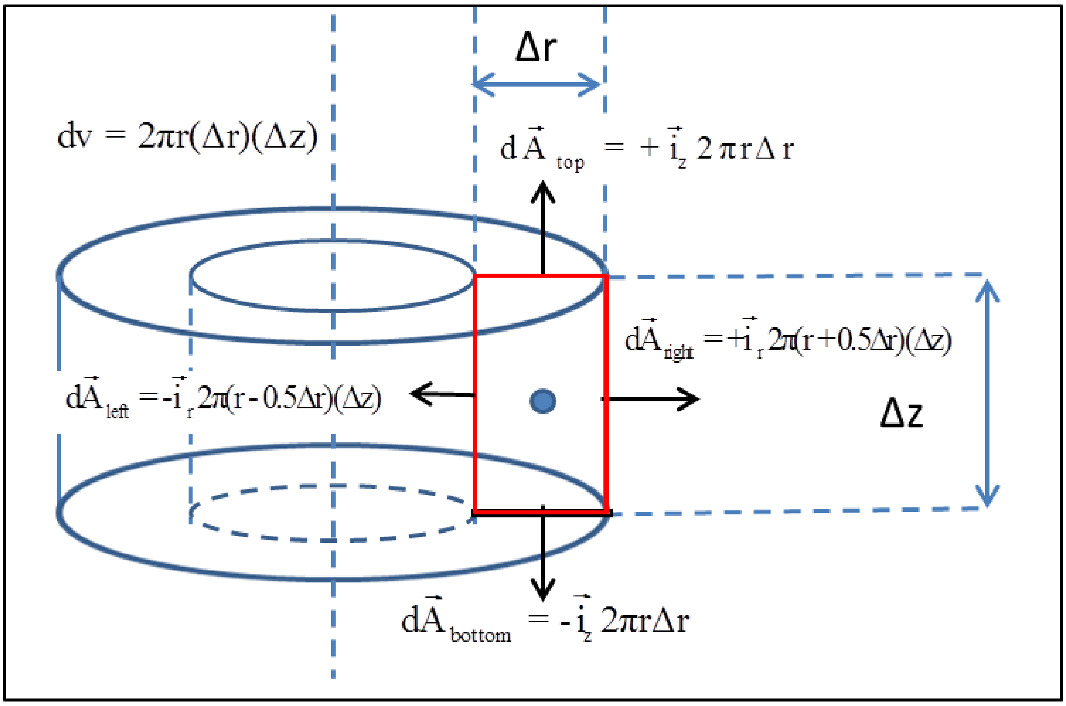
In this system we have axial symmetry: $\frac{\partial}{\partial \varphi} = 0$, so that the gradients can be expressed as follows:

$$\int_{\text{surface}} \left[\vec{i}_r \frac{\partial T_w}{\partial r} + \vec{i}_z \frac{\partial T_w}{\partial z} - \vec{i}_z \frac{1}{\kappa_w} v_z(r) T_w \right] \cdot d\vec{A} = \int_{\text{volume}} \frac{1}{\kappa_w} \frac{\partial T_w}{\partial t} dv \tag{14}$$

$$\int_{\text{surface}} \left[\vec{i}_r \frac{\partial T}{\partial r} + \vec{i}_z \frac{\partial T}{\partial z} \right] \cdot d\vec{A} = \int_{\text{volume}} \frac{1}{\kappa} \frac{\partial T}{\partial t} dv \tag{15}$$

We discretize both regions (water and MH reservoir) with volume elements as the one shown on Figure 4.

Figure 4. An elementary volume element in cylindrical coordinates for a system with axial symmetry. The arrows indicate the directions of the r and the z axes. The magnitude and directions for each surface of the elementary volume are shown.



And we find:

$$\int_{surface}\left[\vec{i}_r\frac{\partial T_w}{\partial r}+\vec{i}_z\frac{\partial T_w}{\partial z}-\vec{i}_z\frac{1}{\kappa_w}v_z(r)T_w\right]\cdot d\vec{A}=\int_{volume}\frac{1}{\kappa_w}\frac{\partial T_w}{\partial t}dv \tag{16}$$

And for each surface of the water volume element we find:

$$\begin{gathered}\int_{left}\left[\frac{\partial T_w}{\partial r}\right]\vec{i}_r\cdot d\vec{A}_{left}+\int_{right}\left[\frac{\partial T_w}{\partial r}\right]\vec{i}_r\cdot d\vec{A}_{right}+\int_{top}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right]\vec{i}_z\cdot d\vec{A}_{top}\\ +\int_{bottom}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right]\vec{i}_z\cdot d\vec{A}_{bottom}=\frac{2\pi r\Delta r\Delta z}{\kappa_w}\frac{\left[T_w(r,z,t)-T_{ref}\right]}{\Delta t}\qquad T_{ref}=T_w(r,z,0^-)\end{gathered} \tag{17}$$

From now on we consider that T is measured with respect to the reference temperature 2 C, and by replacing the different area elements we obtain:

$$\begin{gathered}-\int_{left}\left[\frac{\partial T_w}{\partial r}\right][2\pi(r-0.5\Delta r)\Delta z]+\int_{right}\left[\frac{\partial T_w}{\partial r}\right][2\pi(r+0.5\Delta r)\Delta z]\\ +\int_{top}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right][2\pi r\Delta r]-\int_{bottom}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right][2\pi r\Delta r]=\frac{2\pi r\Delta r\Delta z}{\kappa_w}\frac{T_w}{\Delta t}\end{gathered} \tag{18}$$

Since we deal with an elementary volume element, the integrals for the water region are elementarily evaluated as:

$$
\begin{aligned}
&-\left[\frac{T_W(r,z)-T_W(r-\Delta r,z)}{\Delta r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right]+\left[\frac{T_W(r+\Delta r,z)-T_W(r,z)}{\Delta r}\right]\left[2\pi(r+0.5\Delta r)\Delta z\right]\\
&+\left[\frac{T_w(r,z+\Delta z)-T_W(r,z)}{\Delta z}-\frac{1}{\kappa_w}v_z(r)T_W(r,z)\right]\left[2\pi r\Delta r\right]\\
&-\left[\frac{T_w(r,z)-T_W(r,z-\Delta z)}{\Delta z}-\frac{1}{\kappa_w}v_z(r)T_W(r,z-\Delta z)\right]\left[2\pi r\Delta r\right]=\frac{2\pi r\Delta r\Delta z}{\kappa_w}\frac{T_w}{\Delta t}
\end{aligned}
\qquad (19)
$$

For an element in the methane hydrate region we obtain:

$$
\begin{aligned}
&-\left[\frac{T(r,z)-T(r-\Delta r,z)}{\Delta r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right]+\left[\frac{T(r+\Delta r,z)-T(r,z)}{\Delta r}\right]\left[2\pi(r+0.5\Delta r)\Delta z\right]\\
&+\left[\frac{T(r,z+\Delta z)-T(r,z)}{\Delta z}\right]\left[2\pi r\Delta r\right]-\left[\frac{T(r,z)-T(r,z-\Delta z)}{\Delta z}\right]\left[2\pi r\Delta r\right]=\frac{2\pi r\Delta r\Delta z}{\kappa}\frac{T}{\Delta t}
\end{aligned}
\qquad (20)
$$

When the time interval is chosen to be small enough $(dt \leq 3\,\text{sec})$ this numerical approach yields stable solutions even when the velocity is 1 m/sec.

In Figure 5 we show the results for the EROI associated to the production of methane via hot water injection. The results correspond to a 200x200 spatial node system, and the results were obtained via a Fortran program run on a personal computer. It took 57 seconds of computer time to evaluate the EROI over a time span of 3 hours. We find an EROI [(Energy out) / (Primary energy in)] which varies from a value higher than 30 as the production is started, to a value of 7 after 30 years of production.

Figure 6 shows the time evolution of the applied energy and the produced energy. The applied energy is taken to be only the kinetic energy that must be applied for the water to flow continuously with a velocity v_z:

$$KE=\frac{1}{2}\rho_{water}\left(r_w^2\right)(L_{MH})v_z^2 \qquad (21)$$

The Figure clearly shows the stepwise behavior of the produced energy, as it takes time for the applied energy to heat up each volume element above the melting temperature. As time progresses, it takes longer to heat each volume element since these methane hydrate elements are located at increasing distances from the heating pipe and their volume increases accordingly. Eventually the produced energy will reach a plateau when all the methane hydrate has melted.

The methane hydrate physical characteristics are taken from Gupta et al.[13] and Waite et al [14]. The energy produced is taken to be of the order of 6.1x10+9 joules for each cubic meter of methane hydrate, which dissociates into 160 cubic meters of gas at STP conditions. Data published by Dale et al [15] indicate a methane heat of combustion of 3.868 x 107 joules/m3 , in close agreement with methane energy content of 1000 BTU per cubic foot reported by Speight [16].

Figure 5. EROI determined via Gauss approach. The energy gain is significant over an extended time span. Reservoir: radius=20m, length=500 m. Injection pipe: diameter=1m, length=500 m. Water velocity=1m/sec. Input water temperature=200 C.

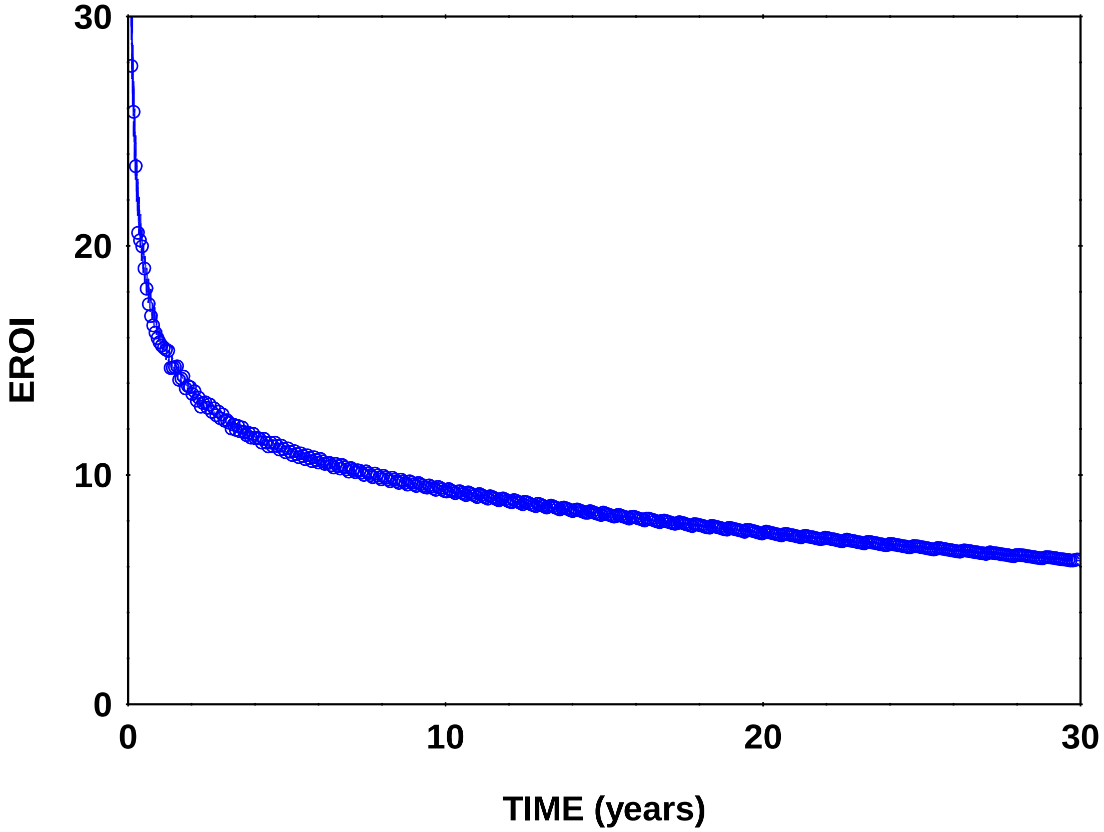
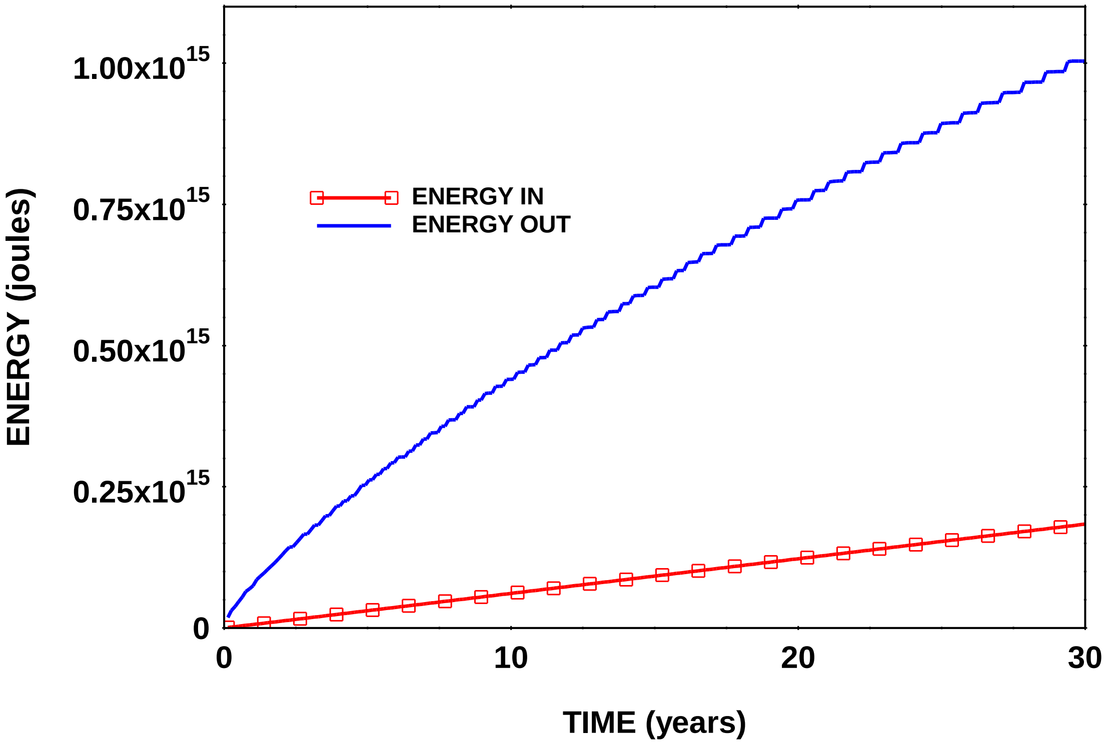


Figure 6. Plots of the applied energy vs. time and the energy equivalent of the melted sections of methane hydrates, for the system indicated on Figure 5.



4. Conclusions

We have considered the change of phase of the solid methane hydrate into water and methane gas when the temperature of each volume element is greater than a melting temperature of 20 C. This is the temperature of the MH phase diagram edge at 1000 meter depths [5]. The results obtained for an initial water temperature of 200 C indicate an EROI [(Energy out) / (Primary energy in)] which varies from higher than 30 as the production is started, to a value of 7 after 30 years of production. The primary input energy was the kinetic energy of the water flow into a pipe of 1 m diameter with a 1 m/sec vel. The thermal energy required to heat the water was assumed to be generated in the cogeneration processes considered in the Japanese production scheme [8].

Speaking ONLY from an energy balance point of view, the partial EROI calculated in this paper – significantly larger than 1 – indicates that methane hydrates represent an important possible energy source.

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Conflict of Interest

The author declares no known conflict of interest.

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