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CALCULATING EROEI FOR THE SREDNJE-VILYUYSK GAS CONDENSATE DEPOSIT*

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Abstract. *In this article we focus on the use of EROEI, or energy efficiency, to compare traditional and non-traditional energy resources. We assess two different methods for calculating EROEI and provide data in support of one method over the other. A description of the selected method is presented using our calculation of the EROEI for the production of gas at the Srednje-Vilyuysk Gas Condensate Deposit.*

Keywords: *peak oil and gas, non-traditional energy resources, alternative energy, energy effectiveness, EROEI*

Energy derived from hydrocarbons is fundamental to contemporary civilization. Currently, fossil fuels provide 85 % of the energy culled from primary energy resources. However, carbon-based energy resources are not renewable, which means that sooner or later we will have to grapple with peak oil, and then with an inevitable decline in the production volume of the other carbon-based energy resources. The first to be affected by this is oil. 2010 saw the publication of a series of analyses dedicated to the problem of peak oil [1 - 3]. The production of oil at a volume of 72 - 75 million barrels a day is expected to continue for another five to ten years, after which we will witness a decline. A report in 2010 by the International Energy Agency (IEA) refers to the "long plateau in oil production", but we must emphasize that this "plateau" is not guaranteed by explored reserves. In fact, the quantity of oil in this calculation dependent on still undiscovered fields is significant. If we exclude the contribution from yet-to-be discovered fields, then we come up with a decline (Fig. 1). Looking further into the future, the problem of decline applies to natural gas, as well. Because of this, we must address the very topical issue of the role played by non-traditional and alternative sources of energy. At present, non-traditional resources encompass the following: gas hydrates, water-dissolved natural gas, gas and oil in tight formations and low-permeability reservoirs, heavy oils, oil sands and natural bitumen, and gases in coal-bearing sediments [4]. As regards alternatives to fuel derived from oil, currently the focus is on technologies for biomass to liquid (BTL), coal to liquid (CTL), and gas to liquid (GTL). In future,

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this list may be expanded if new alternatives are developed. However, we must question the extent to which the given non-traditional and alternative resources and technologies are effected when compared to oil and gas.

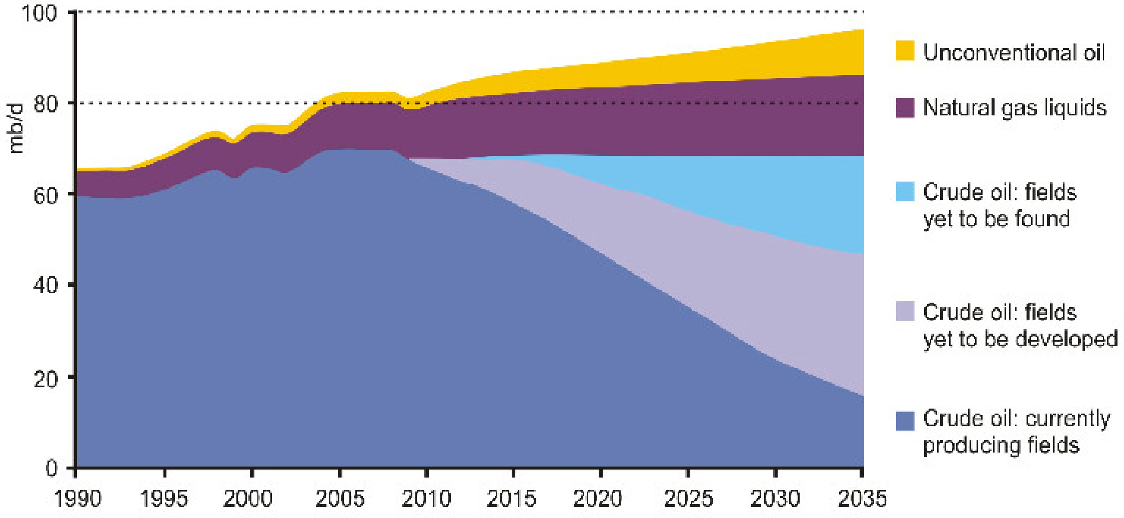

Fig. 1 Forecast for Oil and NLG Production (IEA, 2010)

There have been many different approaches taken when assessing the effectiveness of energy resources [5]. Criteria used include ecological, economic, consumption, and production data. Analyses based on production criteria alone encompasses a range of factors, including EROEI, scalability, the reliability of the resource, and how easy or difficult the extraction process is. EROEI, or energy cost-effectiveness, is one of the most important of these criteria[6]. It is particularly relevant when comparing the technologies used in producing heavy oil with those used in the development of tar sands and the production of natural bitumen. The EROEI calculation for technologies used to process natural bitumen has been provided by the Royal Dutch Shell Company [7].

The concept of EROEI was first introduced by biologist Charles A. Hall in the 1970s in reference to his work on fish migration. At that time he formulated the dictum that “a predator cannot expend more energy in chasing prey than it subsequently obtains from that prey.” Later, he extended this idea to the production of oil as follows:

$$EROEI = E_r / E_i , \qquad (1)$$

where E_r – energy return; E_i – energy invested on production.

From this formula we derive three possible scenarios, each of which is fundamentally different:

1. EROEI = 1 – for each unit of energy received from production, an equal amount of energy was expended. The energy thus produced results in no net gain and is essentially null in terms of results.

2. EROEI < 1 – production of the energy resource is unprofitable in terms of energy produced, and therefore unacceptable.

3. EROEI > 1 – production of the energy resource is profitable in terms of energy produced.

We can also derive the following from the formula:

1. EROEI is independent of the enterprise's financial and economic activities.
2. The value for EROEI depends on the calorific capacity of the energy resource.
3. EROEI depends on the mode of occurrence and the technology used in production of the energy resource.
4. If the energy resource does not have a form of accumulation, then EROEI is dependent on the technology needed to produce energy in the necessary power plants.

The lack of dependency on financial and economic activity is, in and of itself, an important feature in that EROEI and economic indicators do not duplicate each other; rather, they are complementary. Of course, an interdependence between EROEI and economic performance indicators is present. Energy expenditures factor into financial activities; therefore, the lower the energy expenditures connected with production, the greater the financial productivity of the extraction and production processes. It would be completely correct to establish a direct correlation between EROEI and economic results, in which EROEI plays a leading role, as an improvement in EROEI (for example, developing better quality reservoirs or improving production technology) results in an improvement in economic indicators. In contrast, an improvement in economic indicators does not necessarily lead to an improvement in EROEI. Indeed, we can envision a scenario in which the market situation, tax burden, and management practices (theoretically) are such that oil production is no longer economically feasible immediately after the flow stage of the production process. And yet, from the point of view of EROEI, production might still be profitable for some time to come.

Obviously, when comparing various energy resources in terms of EROEI, the same methodology should be used in the calculation for each resource. Charles Hall delineated two methods for calculating EROEI:

1. Basing the calculation on actual energy consumption data as expressed in physical units (tons of fuel, kWh).
2. Basing the calculation on energy intensities. When EROEI is calculated using actual consumption data for a particular field, and the capital investment is known, then the specific energy intensity can be established. Then, using these results, EROEI is calculated for other fields, and for the entire industry.

Hall and others in the U.S. use the latter approach in their calculations. They derived the following EROEI values for various energy resources (Table 1).

Table 1. EROEI for the production of energy resources

Energy resource	EROEI
Oil and gas	35
Natural gas	10
Coal	80
Nuclear power	15
Tar sands	2 - 4
Sugarcane ethanol	0.8 - 10
Corn ethanol	0.8 - 1.6
Biodiesel	1.3

As noted above, by definition EROEI is not dependent on financial and economic results, and maintains this independence. Therefore, it is the opinion of the authors of this article that when calculating EROEI the methodology used should exclude energy intensity from. Results from calculations involving energy intensities are in some cases rather dubious. For example, the low EROEI value derived from the calculation for gas production warrants a closer look. It is well known that gas production is a highly profitable business; therefore a high EROEI value is only to be expected. Thus, it is essential that the calculation be clarified.

Another example of inaccuracy in calculating EROEI using energy intensity is the EROEI value derived for global oil production by Hall and his colleagues. The results and the methodology behind them are presented in the corresponding article [8]. We will briefly examine them here.

Fig. 2 illustrates EROEI values calculating using the following formula:

$$\mathrm{EROEI}\ (t) = E_o(t) / E_i(t), \qquad (2)$$

where E_o – energy obtained;

E_i – energy invested;

t – time period.

Regardless of the method used in the calculation, the dramatic decline in EROEIt in just five years is noteworthy: from 35 to 18 – a decline of almost fifty percent. This is only possible in the event of a substantive, sharp decline in the conditions for excavation and production, which is not the case here. A similar “sawtooth” oscillation in EROEIt of an amplitude of 5 - 10 also raises questions. As noted above, EROEI depends on the resource’s mode of occurrence and the technology used in production. Neither of these factors can change so quickly as to result in multiple declines and increases in EROEI in the space of five years.

The creators of the calculation note that the numerator for the formula is determined rather easily. It is determined from the volume of oil and gas produced, and the calorific value of other extracted resources, all of which are established. However, this is not the case with the denominator. There is no single database of energy expenditures for the oil and gas industry on a global level. Such data is openly available only as regards the U.S. and Great Britain. On a global scale, data is available (and widely used for various purposes) only for financial expenditures in the oil and gas industry. This information is provided by John S. Herold, Inc. (www.ihs.com). The authors were faced with the problem of evaluating energy expenditures for all the remaining oil and gas producing countries. This problem was solved by using the source data for energy and financial expenditures in the oil and gas sectors of the U.S. and Great Britain to derive the energy intensity (EI) of one dollar. The formula for this is as follows:

$$EI = \text{Energy intensities (MJ)} / \text{Monetary expenditures (\$)}. \tag{3}$$

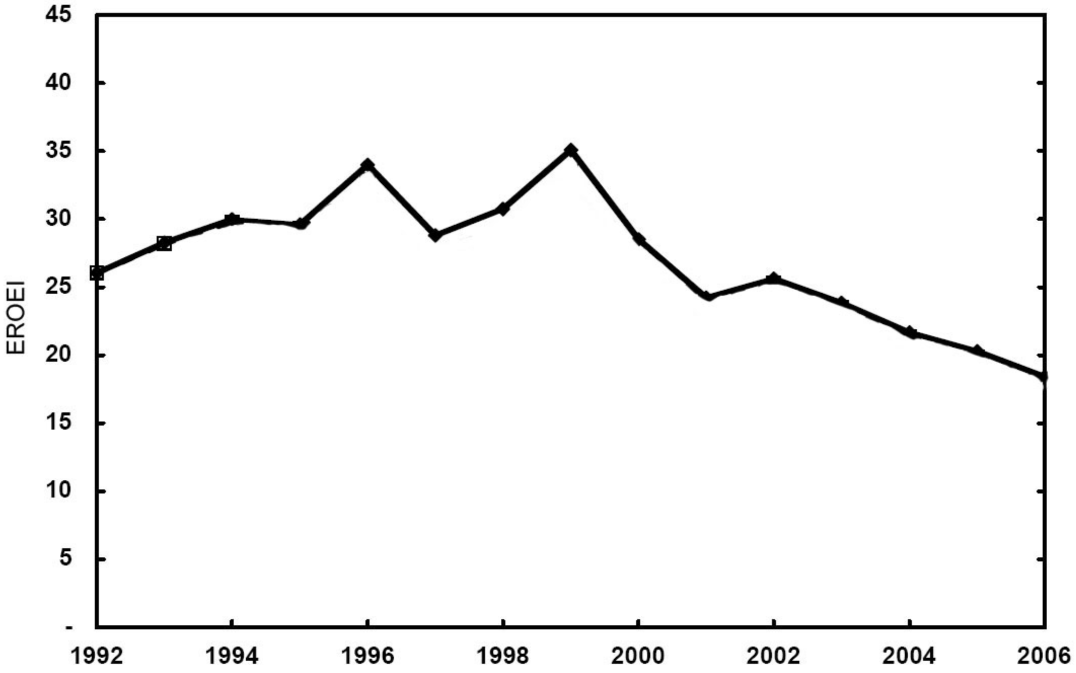

Fig. 2 The EROEI dynamic calculated for global oil and gas production

In 2005 this indicator amounted to 20 MJ per dollar for the U.S. and Great Britain. Further on, the researchers proposed that the same structure and financial effectiveness applies to other oil and gas producing countries. By multiplying the rate found for the total cost worldwide, the final volume of global energy intensities for the oil and gas sector was calculated, which was then used to calculate EROEI.

This resulted in an average value, which, however, also warrants further investigation, in that it resulted in an $EROEI_{2006}$ = 18 for the global oil and gas sector that is not supported by calculations of EROEI for Russia. In contrast to the use of averages, the EROEI for oil and gas production in Russia relied on specific data from the Russian Federal State Statistics Service (Rosstat). In Russian statistics, records are kept for energy resources according to each resource’s use in economic activity. This includes their use in oil and gas production. Using this data, $EROEI_t$ can be calculated (Table 2).

Table 2. Production and use of energy in economic activity

Oil and gas production, Mtoe	**2005**	**2007**	**2008**
Oil	473	491	486
Gas	517	526	534
Direct energy costs:			
electric power	14	17	18
thermal energy	2.8	2.17	2.17
fuel	14	14.77	13.86
$EROEI_t$	**31.7**	**29.9**	**29.5**

The table shows a steady decline in the $EROEI_t$ value of oil and gas production from 31.7 in 2005 to 29.5 in 2008. This gradual decline fully corresponds with the objective conditions in that, as reserves are depleted, the cost of production increases. But, as expected, the decline in EROEI is gradual, without the sharp fluctuations of 5 - 10 in amplitude.

When conducting macro-accounting for any indicator, an averaging-out of results inevitably occurs, and the results of such calculations can serve only as a guide for detecting common features and emerging trends. However, the average in a calculation is patently unsuitable for comparing and forming conclusions about the effectiveness of extraction and production practices in the energy sector, especially as regards diverse energy resources. When comparing, for example, the energy effectiveness of the production of engine fuel from biomass (BTL), gas (GTL), or coal (CTL) using fuel from traditional oil, it is essential that specific comparable data be used, and then that the same method is used to calculate EROEI. There is no place for energy intensity calculations in this process; rather, what is needed are factual data on direct energy costs and data on the materials consumed in the production process.

We will describe a method that uses factual data to calculate the EROEI of gas production at the Srednje-Vilyuysk Gas Condensate Deposit. In so doing, we will compare the effectiveness of gas production with that of the production of other energy resources.

Our first task is to determine the point of calculation of EROEI. In general, we can delineate several production stages in the extraction and processing of energy resources into the final product:

1. Extraction and initial processing of the resource in the field.
2. Transportation.
3. Secondary processing.
4. Storage of the final product.

Some energy resources (for example, coal and gas) do not require secondary processing. From this we derive several points to be included in the calculation of EROEI:

1. At the wellhead.
2. At kilometer zero of the transfer pipeline (at the gate of the pit).
3. At the storage facility for the final product (refinery, processing plant, etc.).
4. At the point where the product is consumed.

Just as with the economic cost, for each resource, depending on the postulated goals, one must select the appropriate point for calculation. If the goal is to compare the energy cost-effectiveness of gas production with the production of other energy resources, then it makes sense to select "kilometer zero" as one point. When comparing the energy cost-effectiveness of extraction and consumption, then a different point of calculation corresponding with this must be selected.

As a base method for calculating $EROEI_{kilometerzero}$ we propose separating total energy expenditures into capital, operational, and cessation of operations:

$$EROEIkz = E / (E_1 + E_2 + E_3), \tag{4}$$

where E – energy returned;

E_1 – energy invested in capital work;

E_2 – energy invested in operations;

E_3 – energy invested in cessation of operations.

Capital energy investments include energy expended on construction of the industrial base, drilling of the well, and creation of the infield infrastructure. Operational energy expenditures include those directly connected with extraction and primary processing of the energy resource. Cessation, or energy invested in dismantling operations includes expenditures associated with the disassembly of all buildings and structures, and those associated with the recultivation of land after completion of field development.

Total energy expenditures are the sum of direct (E^d) and indirect (E^i) costs. Direct energy costs are expressed in tons of fuel (mt), kWh and other energy values. Indirect energy costs relate to energy spent on the production of materials essential to organization of the production process. We thus derive formula 4 as follows:

$$EROEIkz = E / (E_1^{d+i} + E_2^{d+i} + E_3^{d+i}), \tag{5}$$

where $E_1^{d+i} = E^d + E^i$ at the stage of provision of infrastructure;

$E_2^{d+i} = E^d + E^i$ at the operational stage;

$E_3^{d+i} = E^d + E^i$ at the dismantling stage.

Direct energy expenditures (E^d) are listed for each industry, expressed in natural units, with appropriate adjustments made for each industry. Thus, the calculation of direct expenditures avoids any theoretical complications. However, there is a potential practical difficulty relating to the frequent industry practice of calculating the cost of fuel tonnages and electricity collectively, for a group of sites, rather than for each deposit or field on an individual basis. In this study, we used records that are maintained on industrial gas consumption. These records provide data on total gas consumption.

Calculating indirect energy expenditures (E^i), however, is a complicated procedure. Capital works require materials that, in turn, require energy to produce. Tallying up the energy connected with material production, or “embodied energy” is a relatively complicated proposition, requiring the resolution of two theoretical issues:

1. Creating a list of materials which in future will be used to calculate indirect energy costs.
2. Determining a method for converting natural units of these materials into their energy equivalent.

A diverse range of materials is used in industry, and accounting for each kilogram of paint or varnish would be pointless and unproductive. Therefore, we much decide the point, as it were, at which to include materials in our list of calculation. There are various options for determining this. One is to determine the percentage ratio of each item to the total mass of materials. Another approach is to include the materials which, together, make up 90 % of the total volume. We propose to simplify the process by limiting our calculations to basic construction materials, excluding trimming, wood, and granular (sand, gravel, crushed rock) products. Our list consists of the following materials:

1. Steel (structural steel, fittings, sheet metal, etc.).
2. Other metals (aluminum, copper, titanium, etc.).
3. Cement.
4. Bitumen.

These comprise the bulk of material used in any industrial enterprise..

Once the list of materials has been drawn up, the next step is to determine the method for converting this material mass into the energy equivalent. A set amount of energy is expended during the production of each material. Therefore, if we know two parameters for each item on the list, we can calculate the amount of energy used in its production. These two parameters are as follows:

1. The mass of consumed material.
2. The specific energy density in the production of the material.

Determining the mass of consumed materials does not present any theoretical difficulties, as this information is contained in the design documentation and estimates, and also in reports which are compiled for each production facility. In contrast, determining specific energy density used in the production of the materials is a difficult, complex task.

For example, steel production involves a long production chain, beginning with the open pit mining of iron ore, and ending with the storage of the final product. A specific amount of energy is expended at each of these stages. To obtain the final value for the energy expended during the manufacture of, for example, a kilogram of steel, energy expenditures throughout the production chain are totaled. There are examples of this in studies produced in the U.S. and Great Britain. One such study is a report from the University of Bathe entitled "ICE: Inventory of Carbon and Energy" [9]. In their work, the authors analyzed the production of basic building materials in terms of embodied energy and embodied carbon. The study calculated expenditures of primary energy on the production of one unit of each material using a "cradle-to-gate" analysis, which takes into account the energy used during extraction of the raw material, transportation, and in the production process. Table 3 contains the results of this analysis.

Table 3. Specific energy expenditures for the production of construction materials

Item	**Specific energy expenditure, MJ/kg**		
	Average	**Minimum**	**Maximum**
Steel	31.25	6	95.70
Cement	5.08	0.1	11.73
Glass	20.08	2.56	62.10
Aluminum	157.1	8	382.7
Copper	69.02	2.4	152.71
Titanium	470.67	257.84	744.70
Bitumen	47	2.40	50.00

This provides us with the theoretical and methodological basis for calculating EROEI.

To illustrate calculating $EROEI_{kz}$ we focused on the Sredne-Vilyuysk Gas Condensate Deposit, located in the Vilyuysk petroleum region of the Sakha Republic (Yakutsk). The total initial volume of reserves is 147 billion m^3, with 117 billion m^3 in recoverable reserves, 9.2 million tons of condensate, and a volume of recoverable reserves totaling 6 million tons. The Deposit has been in operation for 25 years and has been confined to a local structure of the same name on the Sredne-Vilyuysk dome which complicated the western slope of the Hapchagan structure. The structure is a brachyanticlinal uplift on a sub-latitudinal spread with an area of 34 x 22 kilometers and an amplitude of about 350 m. The Deposit is classified as multi-fallow. Industrial gas flows were obtained from the Taragaiskii reservoir P_2-Ia , from Monomskii beds T_1-II, T_1-Ia, and T_1-I, Kyzylsyrskii bed J_1-1, and the Nizhenevilyuskii J_2-II and Marykchanskii J_2-I formations. The T_1-III deposit layer is the main reserve and is located at depth intervals 2430 - 2590 m. The reservoir capacity ranges from 64 - 87 m marked by sandstones with interlayers of siltstone and argillite. Effective bed thickness is 20 - 63 m, the open porosity of reservoir rocks is 15 - 23 %, and permeability is 0.217 μm^2. The rate of gas flow attains 1543 thousand m^3/day (24 hours). The reservoir pressure is 24.8 MPA, and the temperature is +68 °C. The yield of stable condensate is 62 g/cm^3. The gas-water contact observed in the reservoir is around 2438 m. The deposit is classified as an arched reservoir. The basic project design was developed by the Srednje-Vilyuysk Gas Condensate Deposit, and the calorific value of extracted resources are as follows:

- – Total number of wells – 51, of these:
  - – Production – 42;
  - – Observation – 9.
- – Two gas processing plants.
- – The calorific value of gas according to test results: 35.2 MJ/m$^{3.}$
- – The calorific value of condensate according to test results: 41.5 MJ/kg.

The Deposit has been under industrial development since 1985. Current cumulative volume of production on January 1, 2010 was 26.1 billion m^3 of gas and 1545 thousand tons of condensate. Current annual production is around 1.5 billion m^3 of gas and 75 thousand tons of condensate.

The volume of energy expenditures and mass of capital expenditures on materials for facilities are shown in Table 3.

Table 3. EROEI calculation for the Srednje-Vilyuysk Gas Condensate Deposit

Items, units of measurement	Quantity	Energy intensity 1 unit, GJ	GJ	Mtoe
Capital expenditures, E_1				
Direct expenditures, E_1^d Land clearing and drilling, diesel, mt	20 400	45	918 000	21.9
Indirect expenditures, E_1^i				
Steel, mt				
Production casing, mt	15 161	31.3	473 781	11.3
Industrial flow-lines, mt	10 180	31.3	318 125	7.6
GPP, mt	1 750	31.3	54 688	1.3
Capacitive park, mt	2 600	31.3	81 250	1.9
Cement, mt.	36 750	5.1	186 690	4.5
Total capital expenditures $E_1^d + E_1^i$			**2 032 534**	**48.5**
Operating costs, E_2				
Direct expenditures, E_2^d				
Generation of electrical energy, gas mill.m^3 per year	*10*	*35 400*	*354 000*	*8.5*
Generation of electrical energy, gas mill.m^3 per 25 years	174	35 400	6 159 600	147.1
Production, E				
Annual gas production, mill.m^3	*1 500*	*35 400*	*53 100 000*	*1 268.3*
Gas production per 25 years, mill.m^3	26 100	35 400	923 940 000	22 067.9
Annual production of condensate, thousand mt	*75*	*41 500*	*3 112 500*	*74.3*
Condensate production per 25 years, thousand mt	1 545	41 500	64 117 500	1 531.4
$EROEI_{kz}(t)$				***159***
$EROEI_{kz}$				**121**

Evident from the table is that the bulk of energy costs are expended on operational activities – 75 %, with the remaining 25 % going to capital functions. The $EROEI_{kz}$ (t) value we calculated for one year when considering only operational costs is 159. The $EROEI_{kz}$ value calculated for the industrial development of production totals 121.

Of note is that an $EROEI_{kz}$ of 121 is high, and, in fact, is ten times the value reported in U.S. studies. Moreover, it is ten times higher than the EROEI of alternative energy resources (although, as regards these resources, the calculations need to be refined). However, these findings are completely consistent with the fact that the economic cost of gas production is relatively low, making gas both a highly competitive and highly effective energy resource. After we factor in costs associated with transportation to the energy expenditures we've already established, we find a decline in EROEI to a level comparable with the average value of EROEI presented in Table 2.

An economy that is fueled by highly effective energy resources has an advantage over one in which a significant portion of energy is derived from alternative technologies with a low EROEI (wind, solar energy, biofuels). However, it is important to note that fossil fuels are non-renewable, for which reason we must, nevertheless, develop alternative technologies.

Conclusions

1. The non-renewable nature of energy resources derived from hydrocarbons requires us to explore alternative sources of energy. This, in turn, raises the issue of how to compare the effectiveness of energy resources. EROEI is one approach to this end.
2. Currently, there are two methods put forth for calculating EROEI. One requires calculating direct energy and material expenditures; the second is based on the calculation of energy intensities. The latter method leads to inaccurate results. It follows, then, that if the goal is to compare the effectiveness of the production of energy resources, the first method should be used.
3. When calculating EROEI, capital energy expenditures, operational energy expenditures, and also the energy costs of closing down operations all must be included in the formula. In POL expenditures, electric energy is accounted for directly, whereas with energy expenditures connected with material costs, such as steel and cement, the specific energy intensity used in producing one unit of consumables is used for the calculations.
4. Our calculations for the Srednje-Vilyuysk Gas Condensate Deposit demonstrate that the bulk of all energy expenditures are consumed by operational activity, whereas capital energy expenditures total about 25 %.
5. The high value of 121 which we derived for $EROEI_{kz}$ fully corresponds with expectations when considering the specifics of the industrial production of gas from conventional reservoirs.

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