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INTEGRATED ALTERNATIVE ENERGY SYSTEMS: OIL AS A MODERN LANCE OF PELEUS FOR THE ENERGY TRANSITION

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Resumo
Neste artigo, discutimos a importância de consorciar fontes alternativas com o petróleo. Introduzimos, assim, o conceito de Sistemas Energéticos Alternativos. Estes sistemas integram o petróleo a outras fontes energéticas e criam as condições para novos sistemas energéticos, que se beneficiam do que denominamos, neste artigo, como as "virtudes do petróleo". Estes sistemas produzem vetores energéticos conforme estratégias baseadas na flexibilidade dos insumos e dos produtos energéticos. Há ainda o benefício adicional do incremento do uso de fontes energéticas renováveis através destes sistemas integrados. O conceito de sistemas energéticos alternativos pode trazer uma nova dimensão ao processo de transição da era do petróleo para novas fontes energéticas e pode ajudar na elaboração de políticas energéticas inovadoras para promoção de fontes renováveis.

Abstract

In this viewpoint, we discuss the importance of consorting alternative energy sources with oil, and not of opposing them. That is why we introduce the concept of Alternative Energy Systems, which we feel is broader-ranging and more effective than Alternative Energy Sources, as this deals with the actual transformation process of the global energy system. Alternative energy systems integrate oil with other energy sources and pave the way for new systems, which will benefit from what we call the "virtues of oil". They produce energy carriers for multi-fuel and multi-product strategies, where flexibility is a key target, allied to other co-benefits, especially those related to the increased use of renewable energy sources. The concept of alternative energy systems can bring a new light to the oil transition era discussion and might also influence energy policies for promoting renewables.

1. Introdução

This paper is strongly based on Szklo and Schaeffer [1]. Actually, it is an update of this editorial.

The usual approach for describing and promoting the production and use of alternative energy sources assumes that:

1. These sources must somehow be supported to compete with oil, which is the main primary energy source of today's global energy system.
2. The process for increasing the use of alternative energy sources, even step-by-step, represents the quest for replacing oil in the same way that oil replaced coal in the last century and coal replaced firewood in the XIX century.
3. Among several market barriers for improving the production and use of alternative energy sources, the disregard for the negative externalities of the oil chain is decisive.
4. Oil is a non-renewable energy source and oil reserves are petering out.
5. Oil costs and prices will grow monotonically.

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This conventional approach is useful, but limited and biased. It is limited because it does not consider the whole energy system as a system that integrates energy chains for providing different energy services (e.g. heat, lighting, mobility and so on). It is also biased because it does not consider that some of the barriers for developing alternative energy sources derive from the "virtues", and not from the "vices" of oil. These virtues explain, to a great extent, why oil has become the main driving force for modernity.

The oil chain presents enormous economies of scale and scope. It has important economies of vertical integration (EVI) as well. Oil is crucial not only for driving the energy services of modern society, but also as basic feedstock for producing fertilizers, polymers and lubricants. In some ways, oil not only "feeds and upholds" modern society, but also "build" it.

Although at a different scale, the role played by oil today seemingly differs very little from that of coal during Britain's Industrial Revolution. But this qualitative similarity is no more than appearance. In actual fact, the scale of the goods and services provided by the oil chain is actually far vaster, at costs that are relatively low compared to its competitors.

Some of the keen competitive edge of oil is also due to the fact that its transportation and end-consumption infrastructure is already firmly consolidated. Investments in infrastructure are capital-intensive (resulting in large irreversibility) and normally induce "technological lock-ins" due to the gains associated with the larger number of users of a specific technology or product. The infrastructure "guides" the product.

But even the oil industry infrastructure is partially justified by the "virtues of oil". As a liquid product it is easier to transport than a solid (which does not flow by definition), with higher energy density than a gas. Another important fact is that heat machines, which are the main consumers of oil-based energy products (as well as lubricants and even plastics) meet the requirements of the end-consumers to a large extent, although very inefficient from the thermo-dynamic standpoint and limited to the maximum Carnot cycle efficiency: they can operate well with partial or variable loads, reach full load rapidly, are compact etc.

There is yet another point: the oil industry is global; in fact, it is the only energy industry that is truly worldwide. This endows it with risks but also enormous flexibility, which is reflected in the considerable volume of transactions completed on the oil spot markets.

In brief, some of the difficulties faced by alternative sources attempting to slot into the global energy matrix are due to the "virtues of oil" that are acknowledged by modern societies today (even if not always explicitly, but nevertheless on a daily basis through the consumption patterns of these societies).

But what is really important here are the "problems" associated with the oil chain, which would justify the implementation of alternative sources, other than oil. The first problem facing the modern oil industry is oil scarcity. In this respect, some recent studies suggest that the world's "conventional" oil production capacity is reaching its limits (Campbell and Laherrere [2]; Laherre [3]; Bentley [4]; Deffeyes [5]; Campbell [6]). Nevertheless, some authors disagree with these projections. For instance, Adelman [7] believes that the ultimate (physical) limits of the reserves are irrelevant, because the price will rise so steeply as they reach utter depletion that demand will fade away before the full physical depletion of this resource. Similarly, the conventional oil concept is not rigid in terms of time, but rather varies as technological progress lowers the production cost of oils once rated as non-conventional. Moreover, oil price hikes underpin the feasibility of new production areas, strengthened by the geopolitical dynamics of the industry, justifying its quest to diversify sources of supplies and making it less vulnerable.

Therefore, over the medium term, the problem of oil scarcity is less important than the issues of access to reserves and oil prices. For instance, a relevant driving factor for oil vulnerability is related to chokepoints. Nevertheless, it is always important to recall that oil prices are far higher than its marginal production costs. In contrast to its possible alternative energy sources, oil generates huge Ricardian rents. In other words, there is room to prune oil prices, based on a strategy focused more on re-establishing market shares by the producer and exporter countries, which is not the case with other energy sources over the short and even perhaps the medium terms.

Finally, we come to the crux of the oil chain problems, which are its negative externalities. Particularly noteworthy in this case is the problem of Global Climate Change and emissions of greenhouse gases caused by fossil fuel consumption. Oil is the world's main primary source of both energy and hydrocarbons. Much of these hydrocarbons are used to release chemical energy through combustion reactions in low-efficiency heat machines. The quest here thus focuses on the "decarbonization" of energy systems through the shift to an economy based on hydrogen and/or bio-fuels.

But can this transition take place without oil? Or without clashing with it? Will this transition follow in the footsteps of earlier shifts from fuelwood and charcoal to coal, or from coal to oil, where technological innovations focused on primary energy production resulted in learning economies and crucial modifications to energy infrastructures? We believe not. For this to occur, the transition should be based more on modifications to the infrastructure (organizational changes) rather than incremental alterations in technology (or prototypes). What is actually noted is that oil infrastructures are the driving forces behind the well-being of modern society.

Thus, the "virtues of oil" tend to make this transition not a process that offers an alternative to oil, but rather a process in which oil still plays a leading role. However, oil should gradually fade into the background, leaving room for the newcomers. This is why we suggest that this process be called a transition to “alternative energy systems” rather than the introduction of “alternative energy sources”. It should be noted quite clearly here that alternative sources are not excluded from the process, but they are introduced through oil, rather than in opposition to it. Through its consolidated infrastructures, it is oil that establishes the scale required for the introduction of new energy sources. And in order for this to occur, ultra-versatile energy complexes must be established, based, firstly, on synthesis gas production (Williams [8]).

2. Alternative energy systems – Gasification and Syngas Production

Alternative energy systems incorporate advanced technologies that may have feedstock flexibility and allow for various combinations of electricity, liquid fuels, hydrogen, chemicals and/or heat (Yamashita & Barreto [9]).. They are based on the production of synthesis gas (hereinafter called syngas), a mixture of hydrogen and carbon oxides that can be generated by a variety of processes and feedstocks (oil, coal, biomass, natural gas) and can be transformed into a number of chemicals and/or energy carriers. In such systems, syngas operates as the key enabling energy carrier for the multi-fuel and multi-product strategy. Syngas can be obtained from different feedstocks, allowing their conversion into higher quality, cleaner and more flexible energy carriers. This means also that it can change the way oil is classified, since conventional and non-conventional (or ultra-heavy crudes) can be used as feedstock for gasification processes.

To produce syngas in a refinery, heavy liquid fractions are partially oxidized (gasification), including vacuum wastes, visco-reduction wastes, and heavy oil wastes (Ashizawa et al. [10]). The main requirement for gasification process feedstock is its carbon and hydrogen content, so that its conversion produces syngas (CO and H_2) in the proportions desired by the refiner. Consequently, gasifying oil wastes in refineries is basically an integrated process involving the following stages: preparation of the feed, gasifier, air separation (supply of oxygen to the gasifier), purification of the syngas, sulfur recovery and optionally, combined cycle cogeneration (gas turbine and steam turbine) and hydrogen production maximization (through water-shift reactions).

But, if syngas can be produced from coal, oil, natural gas, biomass, or any hydrocarbon, why stress here a process that basically consists of gasifying oil mingled with other hydrocarbons?[1] The initial answer lies in the oil refining requirements for the near future. To an increasing extent, oil refining must deal with the challenge of introducing wastes gasification processes in order to produce syngas because:

- As refineries become more complex and more versatile, they must also introduce bottom-of-barrel processes, particularly delayed coking that generates heavy wastes. These heavy wastes must be disposed off or will be traded, normally, at low price. Therefore, bottom-of-barrel processes increase the feedstock for gasification.
- Gasification reduces the solid and liquid wastes produced by a refinery. Most gasifiers produce elemental sulfur and vitrified slag. This issue is becoming important due to the increased interest in low-quality petroleum pitch/petcoke utilization, and because of mandates for more recycling and less solid waste disposal.
- Crudes feedstocks with higher sulfur content levels hamper the process and make it harder to meet increasingly stringent oil product specifications. When combined with Fischer-Tropsch synthesis processes, wastes gasification processes may generate high-quality synthetic liquids, particularly diesel, naphtha and jet fuel. This even justifies the production of synthetics to blend fuels at the refinery (e.g., zero sulfur, high cetane F-T diesel could be used as a blending stock to assist refiners in meeting ultra low sulfur diesel specifications).
- Prompted by increasingly heavy acid oils, the need to add hydro-treatment and deep conversion processes will increase hydrogen demands to a considerable extent. The relative cost of producing hydrogen from solid wastes (gasification), compared to natural gas (steam reform) is very sensitive to natural gas prices. As some solid wastes have a negative cost to the refiner (or must be shipped and disposed of at solid wastes dumps) the trend is for gasification to move steadily ahead as a widely-used process for producing hydrogen in refineries.[2]

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1 Oil process that basically takes place in what we call the “refinery of the future”, integrating the refinery as it is conceptualized today with other energy systems through advanced gasification systems (for example through integrating biomass and heavy solid oil wastes gasification systems). The “refinery of the future” may produce syngas, CO and H_2 that could meet its own hydrogen and heat requirements, while generating electricity through combined cycle power generation, or could be shipped to a synthetic fuels production plant.

2 In addition, regulations on gasoline aromatics composition are constraining catalytic reformer operations and removing one of the most important sources of hydrogen traditionally available in complex refineries worldwide.

The second answer to the question posed above lies in what we called the “virtues” of oil: scale and infrastructure. Today’s refineries are major hydrogen takers as well as electricity and heat (or fuel to generate heat). In quantitative terms, refineries are the world’s main industrial plants for producing and consuming hydrogen.

In brief, the following situation is noted in the global refining industry:

- Rising output of solid wastes due to processing heavy oils and adding delayed coking plants;
- Higher hydrogen demands from HCC and HDT units.

Solving this situation naturally includes gasifying heavy solid wastes at the refineries. This explains why gasification projects worldwide have focused on petroleum refining, many involving the trigeneration of hydrogen, power and steam; and the fuel of choice for new gasification projects is low-quality petroleum pitch and petcoke (around 45% of current gasification projects) – Marano [11]. Moreover, most of the newer European gasification projects, in the 1990s, were large oil refinery polygeneration projects that involve major upgrades of refineries to reduce production of heavy fuel oil (SFA Pacific [12]).[3] In 2003, some forty refineries in the USA – with an output of over 1,000 tons a day of petcoke – were candidates for installing gasification units. This same year, the existing and planned gasification plants at refineries in the USA totaled almost 4 GWe (Marano [11]). Moreover there were some 10 GWe installed worldwide in 2001 in oil and oil products gasification projects (NETL [13]). Additionally, recent projects include U.S. refineries in El Dorado, KS (Frontier Oil, formerly Texaco), Coffeyville, KS (Farmland Industries), Delaware City (Motiva), and Baytown (ExxonMobil); and European refineries in Falconara, Italy (API), Sicily, Italy (ISAB), Sardinia, Italy (Sarlux), and Pernis, the Netherlands (Shell) (Marano [11]; Worrell & Galitsky [14]). For instance, Shell refinery in Pernis (Netherlands) treat residues from hydrocracker to generate 110 MWe of power and 285 tonnes of hydrogen; IPA Falconery refinery (Italy) uses IGCC to treat visbreaker residues to produce 241 MWe (Worrell & Galitsky [14]).

Another interesting point refers to the technological development of hydrocarbon gasification that has been conducted by oil companies. Indeed, the experience around the world indicates a preference for entrained bed gasifiers (Texaco and Shell gasifiers) over the BGL and KRW gasifiers (NTEL [13]; Zheng & Furinsky [15]). In addition, entrained bed gasifiers allow feedstock flexibility. For instance, Texaco gasifier (slurry mode) is suitable for gasification of molten feeds such as distillation residues. This also suggests that entrained bed gasifiers can function as incinerators of organic waste (Zheng & Furinsky [15]). The surge in refinery polygeneration projects also helps the Texaco and Shell technologies, as both are well known in industry and are quite experienced with processing low-value refinery feedstocks (SFA Pacific [12]).

Consequently, oil company investments in gasification plants processing heavy oil wastes (particularly petcoke) have been proven justified over the past ten years, regardless of the transition to a hydrogen economy, or even the formation of the so-called “alternative energy system”. This is a “natural’ demand from a global refining industry that is increasingly complex. In general lines, the gasification process is integrated with other plants at the refinery, consuming their solid wastes and producing the hydrogen required for the hydro-conversion and hydro-treatment processes, as well as some of the electricity required by the refinery.

However, the development of oil wastes gasification units and the production of syngas at highly-complex refineries, even if not directly motivated by the alternative energy systems, create the conditions required for their formation. This paves the way for a technological learning curve with an increase in the production scales of hydrogen and synthetic products based on the Fisher-Tropsch route.

Moreover, when hydrocarbon gasification and integrated hydrogen production are carried out at refineries, they benefit from the related operating scale and product storage capacities. To an increasing extent, these are energy and non-energy production centers whose blending includes the addition of non-conventional or alternative products such as the synthetic liquids produced by the Fisher-Tropsch route and biofuels. Consequently, what is known as the “refinery of the future” is in fact growing into an integrated alternative energy system, a complex for poly-energy generation, particularly ultra-specified fuels based on a variety of energy feedstocks.

This alternative energy system includes several different types of feedstock other than oil, producing a broad range of energy products (fuels and electricity) as well as non-energy items (chemical and petrochemical products). Furthermore, this system allows the sources that are today called “alternative” (such as biofuels) to build up scale by benefiting from the oil chain scales. It is through this system that the transition from oil can be implemented, rather than working against it. It is here that the concept of substitution can be deployed, introducing aspects related to flexibility and scale.

However, some challenges still remain for implementing alternative energy systems:

- Gasification of hydrocarbons is more complex than the direct combustion. In the case of a multi-fuel equipment, problems of corrosion and toxic emissions may also arise.

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3 In the past, there were strong markets for low quality (high sulfur and metal) heavy fuel oil as power plant fuel, especially in Southern Europe. Today, deregulation of power generation throughout Europe and tough new emission regulations in Southern Europe are triggering major changes in European power generation and oil refinery production.

- Multi-fuel gasifiers are not fully developed. R&D issues include (Stiegel and Maxwell, [16]):
  - Capital cost reduction and process integration of Air Separation Units (ASU).[4] These units are very intensive in capital and operating costs, usually accounting for more than 15% of total plant capital cost, while consuming substantial amounts of electricity for air compression. One novel approach is the use of high temperature mixed-oxide ceramic membranes. It is expected around 30% reduction in the capital cost of the ASU, owning to this concept.
  - Feedstock preparation advanced processes in order to allow co-feeding
  - Gas cleaning advanced processes and advanced sulfur recovery concepts
  - Advancements in flexibility and adjustment of syngas composition: the production of more than one product offers the unique opportunity to adjust swings in market demand for products, while maximizing the utilization of capital investment. For instance, for optimizing the diesel production, the preferred Fisher-Tropsch (F-T) route, after the production of the syngas in the gasifier, is the Low-Temperature FT. However, the optimum syngas for the low-temperature F-T process should have H_2/CO ratios slightly higher than 2 v/v and a low content of CH_4 and CO_2 (<3% v/v in the dry Synthesis Gas). These syngas characteristics would allow the achievement of the highest overall carbon efficiency combining high conversion per pass in the F-T reactor with good selectivity towards the desired liquid products. Partial oxidation of petcoke does not provide the most suitable H_2/CO ratio, however.
  - Drastic reduction of contaminants allowing the integration of the gasifier with fuel cells (depends on near zero contaminants syngas)
  - Advanced hydrogen separating and cleaning units.[5] A very promising approach is the use of high temperature ceramic membranes, which affects the WGS reaction in the syngas stream while simultaneously separates H_2 (the removal of H_2 favorably affects the equilibrium conversion of the WGS reaction, thereby producing more H_2 than would otherwise be achieved in the absence of this removal) .
  - Advanced CO_2 separation units (including co-capture of CO_2 and H_2S).
- The cost of an oil residue gasifier is still high. It is more expensive than a deep hydroconversion unit. It hovers between 800 and 1000 million US$, for gasifiers operating at 70-120 bar outputting around 1000 MWth of hydrogen (LHV) – Kreutz et al. [18]. Data from five European refineries that are currently running at IGCC plants indicate the fixed cost of around 2,000 US$/kW (IGCC plants with thermal efficiency of 40% and close to 99% sulphur emission abatement) – EIPCCB [19]. The cost differential related to fuel prices is not still sufficient to pay back the added capital of the gasification plant. An acceptable return on the investment can be realized only when very-low cost feedstocks are available, the local cost of natural gas is high, and the technology is integrated with existing facilities at the refinery. Steam reforming of methane usually produces hydrogen at lower cost than partial oxidation of heavy fuel oil, if the cost of methane is less than about 65% of fuel oil on an energy basis. Therefore, additional efforts in R&D&D are necessary in order to reduce the cost of these equipments. In addition, as average electrical demand in a refinery is usually less than 80 MWe, the investment in gasifiers for IGCC plants (co-producing H_2, steam/heat and electricity) often depends on the opportunity to export the surplus electrical power generated.
- The last issue is particularly true for multi-fuels gasifiers, due to the fact that different technologies are being tested for different feeds. In fluidized bed gasifiers, solid fuels tend to burn (or react) more homogeneously (the bed acts as a boiling fluid), and the heat rate is higher. It also reduces the cost for adjusting the particle size of the feed, which is a key-parameter for solid fuels. Nevertheless, the most tested technology for oil residues is based on entrained bed gasifiers for slurry (Texaco) or dry feed (Shell). This option allows better temperature control (DOE [20], Zheng and Furinsky [15]). Yet, although entrained bed gasifiers were firstly developed to be used in refineries, they were also used for the gasification of coal (Worrell and Galitsky [14]).
- Biomass use in an energy complex depends on its availability, which, in turn, depends on season. The transportation infrastructure also must be improved.
- The Fisher-Tropsch synthesis is the commercial route for producing synthetic fuels from syngas. In this case, technically natural gas is the most suitable feedstock for the FT synthesis. Natural gas auto-thermal reform provides H_2 to CO molar ratios ranging from 2:1 to 3:1, while oil residues, biomass or coal partial oxidation produces syngas with H_2 to CO ratio of less than 0.7:1 (Marano and Ciferno [21]). For these feedstocks, water gas shift reaction has to be used to adjust the H_2 to CO ratio.

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4 ASU is normally a stand-alone unit generating >95% pure oxygen at atmospheric pressure.
5 Normally, it is used a Pressure Swing Adsorption Unit (PSA), which produces high purity hydrogen (99.999%). It operates normally at 20 bar and reaches separation efficiencies in the range of 85-90% (Chiesa et al. [17]).

Finally, in the transition from the “oil economy” of the XX century to the “decarbonized economy” of the XXI century, it is not only the rising use of biofuels that will be important, but also the retention of carbon emitted by fossil fuels. Here also, the implementation of alternative energy systems at oil refineries becomes crucial. In practice, a conventional refinery has a large numbers of process heaters scattered around its site, making CO_2 capture difficult or expensive (Phillips [22]). Gasification allows a single point of source and capture of CO_2 in the refinery, while it produces syngas and utilities. Moreover, the CO_2 uptake processes through chemical absorption in amines or physical adsorption in Selexol are easier in the gasifier (where concentrated CO_2 streams are produced) than in the conventional combustion equipment exhaust systems in the refineries.

Even if this alternative energy system does not offer a full response to the problem of Global Climate Change, gasifying petcoke may ease the global environmental impacts of the oil industry over the short term. For the short to medium term, gasifying petcoke with other hydrocarbons through consolidating the alternative energy system ensures the feasibility of wider use of alternative sources (particularly gasification biomass) and the formation of flexible energy and non-energy product fabrication structures, fostering the transition to a possible “hydrogen economy” over the medium to long term.

3. Final Remarks

As of today, the increased demand for lighter products and increased use of conversion processes is followed by an increased stream of heavy bottoms and residues. Gasification of theses residues and coke to produce synthesis gas is a promising option. The state-of-the-art gasification processes use oxygen at high temperature in entrained bed gasifiers. Due to limited oxygen in reaction, heavy hydrocarbons are converted to synthesis gas, sulphur is easily removed as H_2S and electricity can also be produced in IGCC plants.

Oil will be the main player in the ongoing energy transition, in contrast to other primary energy sources that were highly significant in the past but that lost importance as new energy sources were introduced. Consequently, it is vital to include oil in the “dynamic equation” describing the transition to a “more decarbonized” economy. It is vital to ensure that the virtues of oil cease to be barriers to alternative sources and instead become agents that usher in these same alternative sources. When mingled with oil, these so-called alternative sources gain through technological learning curves, in parallel to economies of integration, scope and scale, and do not run up against the technological curbs imposed by the existing infrastructure in the global energy system. At the same time, the integration of oil with alternative sources will definitively reduce the market power that light crude oil producers currently have in the international market, also benefiting the energy transition.

Speaking quite strictly, alternative energy sources would no longer be sources of energy that compete with oil over the short term, but would rather constitute feedstock for integrated alternative systems, complementing, first, and replacing, in the long term, oil. And in this process, oil appears as a modern Lance of Peleus, a contemporary sword that both cuts and heals.

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5. Referências

[1] Szklo A. Schaeffer R. Alternative energy sources or integrated alternative energy systems? Oil as a modern lance of Peleus for the energy transition. Energy – the International Journal. Editorial accepted in 2005. Available on line (www.sciencedirect.com) since 1995.
[2] Campbell C. Laherrere J. The End of Cheap Oil. Scientific American 1998, March: 78-83.
[3] Laherrere J. Hubbert’s Peak: The impending world oil shortage. Int. J. Global Energy Issues 2002; 17(4): 360-382.
[4] Bentley R.W. Global Oil & Gas Depletion: An Overview. Energy Policy 2002; 30 (3): 189-205.
[5] Deffeyes R. Lognormal Curves applied to the oil industry. J. Petrol. Technology 2002; 49 (1): 33-36.
[6] Campbell C. Forecasting Global Oil Supply 2000-2050. Hubbert Center Newsletter 2002; 3, July: 1-8 (www.hubbertpeak.com/campbell; accessed on April 10th, 2004).
[7] Adelman M.A. World Oil Production & Prices 1947-2000. The Quarterly Review of Economics and Finance 2002; 42 (2): 169-191.

[8] Williams B. Refiners' Future Survival Hinges on Adapting to Changing Feedstocks, Product Specs. Oil & Gas Journal 2003; Aug: 20-34.
[9] Yamashita K, Barreto L. Energyplexes for the 21st century: Coal gasification for co-producing hydrogen, electricity and liquid fuels Energy 2005; 30: 2453–2473.
[10] Ashizawa M, Hara S., Kazuhiro K., Inumaru J.. Gasification characteristics of extra-heavy oil in a research-scale gasifier, Energy 2005; 30: 2194–2205
[11] Marano J. Gasification and supporting technologies – Refinery Technology Profiles. NETL – Technical Report. 53 p. Ridge, Tennessee: ORNL, 2003.
[12] SFA Pacific. Gasification—Worldwide Use and Acceptance. Report prepared by for the U.S. Department of Energy, Office of Fossil Energy National Energy Technology Laboratory and the Gasification Technologies Council (Contract DE-AMO1-98FE65271), 2000.
[13] NETL. Gasification Worldwide Database, 2001.
[14] Worrell E, Galitsky C. Profile of the Petroleum Refining Industry in California. California Industries of the Future Program. Energy Analysis Department. Environmental Energy Technologies Department. Berkeley, 2004.
[15] Zheng L., Furinsky E. Comparison of Shell, Texaco, BGL and KRW gasifiers as part of IGCC plant computer simulations. Energy Conversion and Management 2005; 46: 1767–1779.
[16] Stiegel G. Maxwell R. Gasification technologies: the path to clean, affordable energt in the 21 sc century. Fuel Processing Technology 2001; 71: 79–97
[17] Chiesa P. Consonni S. Kreutz T. Williams R. Co-production of hydrogen, electricity andCO2 from coal with commercially ready technology. Performance and emissions. International Journal of Hydrogen Energy 2005; 30: 747 – 767
[18] Kreutz T. Williams R. Consonni S. Chiesa P. Co-production of hydrogen, electricity andCO2 from coal with commercially ready technology. Economic analysis. International Journal of Hydrogen Energy 2005; 30: 769-784
[19] EIPPCB. REF_final draft. Version October 2001. European Comission.
[20] DOE. Coproduction of Power, Fuels and Chemicals – CCT Program. Topical Report Number 21 September, 2001.
[21] Marano, J. Ciferno, J. Life-Cycle Greenhouse-Gas Emissions Inventory For Fischer-Tropsch Fuels. Technical Report Prepared for U.S. Department of Energy National Energy Technology Laboratory. June 2001
[22] Phillips G. CO_2 Management in Refineries. Technical Paper. Gasification V. Noordwijk. 2002.