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TECHNOLOGICAL INNOVATIONS FOR ECOLOGICALLY SUSTAINABLE DEVELOPMENT: The Case of the Chemical and Energy Industries in the Context of Energochemical Systems Technologies Development

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FOREWORD

The Integrated Energy Systems (IES) Project at IIASA has a wide range of collaborative organizations in many countries involved in developing effective energy use and emission clean energy systems for the next century. This paper describes preliminary results of assessing the effects of integrating the energy and chemical industries in Poland. This is done on the basis of two coal and lignite conversion technologies (PYGAS and PYREG), taking into account specific economic and social conditions. Results obtained by the authors and presented in the paper show the good economic prospects for improving existing industrial systems by introducing the new coal technologies.

Vassili Okorokov
Leader, Integrated
Energy Systems

PREFACE

This paper is aimed at the identification and evaluation of various development paths for the energy and chemical industries. This is to be embeded in the broader philosophy of the so-called Ecologically Sustainable Development (ESD). We focus our attention on the Polish energy and chemical industries since their development seems to be one of the key factors within the context of ESD.

Assuming a strategic option described by Häfele (Novel Horizontally Integrated Energy Systems – NHIES) as a tartet structure for the next century, we present various development alternatives which may be paths leading to the target. This view if one of the results of our research in the field of development for the chemical industry in Poland.

As this research is regionally oriented, we take into consideration the possibilities of utilizing two coal and lignite conversion technologies (PYGAS and PYREG). We show their reliability within the ESD context when these technologies will be introduced in the chemical and energy and power industries.

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TECHNOLOGICAL INNOVATIONS FOR ECOLOGICALLY SUSTAINABLE DEVELOPMENT

The Case of the Chemical and Energy Industries in the Context of Energochemical Systems Technologies Development

Maciej Zebrowski and Pawel Rejewski

1. INTRODUCTION

Throughout history man always faced the problem of limited resources. A cave man had to hunt for animals within his walking range. Thus his potential food resources were limited. Similarly, when he started to develop agriculture, his ability of food production by means of agriculture was limited by primitive tools and his physical strength. Improvements in the efficiency of the means of production, however slow throughout history, evolved in response to limited resources. The progress was achieved by enlarging amounts of accessible resources, by discovering new resources, by better utilization of already existing and exploitation of new resources [*Dobrowolski et al., 1980*].

Technological development has not only allowed man to conquer the earth but has led him to change it dramatically.

The qualitative change which evolved over time within this general framework is the scale of operation of today's "civilized world" and that is considered as enormous. But, not disregarding the weight of this factor, it seems relatively overexposed by common wisdom due to limitations of our present knowledge and imagination of how the development deadlocks could be eliminated. In fact the phenomenon of stress and fear resulting from these limitations is a permanent factor of life from the beginning of the human race. The ability to produce made us masters of the world. We may say that production and technological structure form an adaptive mechanism necessary for a man to change and follow the changing world. But at the same time this makes us slaves of technological development. In fact, it is the permanent presence of stress which provides the pressure necessary to force the human race through "trial and error" paths to new developments which push away a frontier of constraints to development.

What are the technological constraints and opportunities that have become increasingly important during the course of economic development? First, the growing gap between the rich and the poor, as well as the gap between well informed (armed in know-how technology) and not informed who are left behind times. Second, the acceleration in technological development together with the fact that decisions concerning investment and resource allocation (which we call root decisions) have a growing impact on our world and their irreversible effects last over a growing time span. Third, the rising number of resources that become limits to development. Among these resources environment attained the leading position.

This paper is aimed at identification and evaluation of the development path to the desirable energy perspectives projected for Europe. This is to be embedded in the broader philosophy of the so called Ecologically Sustainable Development (ESD). We focus our attention on energy and chemical industries since their development seems to be one of the key-factors in the ESD context. This view is one of the results of years of our research in the field of the development of the chemical industry.

We should focus on potential "transforming technologies", i.e. those whose impact could lead towards ESD.

In this paper we take as a point of departure a strategic option described by Häfele and his colleagues in (*Häfele et al., 1986*). This option is based on the concept of Novel Integrated Energy Systems (NIES) with zero emission. The notion of NIES is based on energochemical processing of fossil fuels integrated with nuclear energy production. The basic idea behind such an integrated system is to decompose and purify the primary fossil energy inputs before combustion and to allocate the decomposition products stoichiometrically in line with the requirements for final energy. By this we achieve a horizontal integration of different energy sources similar to the one in the electricity generating system. If Häfele's concept is to be considered as an ideal energy system of the next century, then the question arises: what development alternatives would bring about a path to reach it? There may be many paths leading to the target. In this paper we enter the first stage of research to explore various possible trajectories, in order to examine the technological opportunities and constraints to attaining NIES.

From this stems the thesis of research reported in this paper. It can be formulated as follows.

> Let the NIES concept be a target structure. By evaluation of various trajectories leading to it, its attainability can be verified in terms of concept, scale of applicability and time. This should be done in practical terms in the context of regional conditions and possibly through various case studies. The process of evaluation will not only concern technological development, but, as an integral part of it, various policies and strategies of development can be exercised.

We consider and offer for discussion an approach which assumes working out alternative development trajectories. This is supported by the analysis carried out through the following close-up. We start from the case of Europe and take SO_x emissions as a pivoting factor. Moreover, we take into consideration coal and lignite extraction and their processing as a main source of the devastating emission of SO_x. At present this damaging impact comes mainly from the contemporary methods of combustion of the above fossils for generating secondary energy. An overview of the coal and lignite problems in Europe is taken in the broader context of interactions with crude oil and gas industries.

We characterize the scale of the "coal and lignite problem" together with some forecasts and estimates of relevant emissions. In our discussion we focus on some specific technologies. One example concerns coal treatment (PYGAS) and another lignite treatment (PYREG). The above innovations are examined in the context of the Polish economy, its natural resources base and its environment. Our aim is to investigate how the adoption of these technologies could effectively relax environmental constraints and expand economic opportunities to enable development of the chemical and energy sectors, and so open a path to a NIES future. Other relevant technologies are also expected to be evaluated at the next stage [*Babcock Interim Report, 1986*; *Nietchke, 1986*].

Several examples of a potential penetration of the discussed technologies into both sectors, treated integrally, are outlined. At the same time they provide an example of an important "technological policy exercise".

In conclusion we aim at proposing the continuation of research which follows the main stream presented in the paper.

2. COAL AND LIGNITE IN EUROPE - AN OVERVIEW

2.1. General Deposits and Extraction Data

Europe with very few exceptions (Great Britain, Norway, Soviet Union) is very poor in crude oil deposits. As a result both East and West European economies are based on imported crude oil.

The role of solid fuels - coal and lignite - has been very important to the evolution of energy systems in Europe. Although the role of nuclear energy is growing, it can be expected that conventional power stations will exist till the first half of the next century [*Marchetti and Nakicenovic, 1979*]. A growing demand for energy may still support this trend. Moreover, after the year 2000 supply of natural hydrocarbons may decrease due to their exhaustion. According to *IEEC* [*1985*], coal and lignite deposits in Europe can be presented as in Table 1. Our considerations put more emphasis on lignite since, in our opinion, this resource is much less explored and known to the public than coal.

Table 1. Recoverable Reserves of Coals in Europe (end of 1985).

	Hard Coal Bituminous/Anthracite (million tce)	Brown Coal Subbituminous/Lignite (million tce)
Western Europe		
France (incl. Monaco)	298.5	19.2
Greece	-	465.0
Spain	651.0	246.9
Turkey	126.0	518.4
United Kingdom	7500.0	225.0
Germany, Federal Republic	22439.3	10545.0
Yugoslavia	52.5	4950.0
Others	910.5	5011.5
Total, Western Europe	31977.8	22042.5
Eastern Europe		
Bulgaria	22.5	1110.0
Czechoslovakia	2025.0	858.0
German Democratic Republic	-	7500.0
Hungary	168.8	1200.0
Poland	20250.0	3600.0
Romania	37.5	330.0
Total, Eastern Europe	22503.8	14598.0
Total Europe	54481.6	36640.5
USSR	81750.0	39600.0
Total Europe and the USSR	136231.6	76240.5
World	395940.8	127969.5

SOURCES: *BP Statistical Review of World Energy*, June 1986; *UN Energy Statistics Yearbook*, 1984; *Survey of Energy Resources*, 1980.

Conversion factors:

Hard coal 1 MT = 0.75 tce, and

Brown coal 1 MT = 0.30 tce.

This emphasis is in proportion to lignite's potential value for Europe. In fact, according to the above source, 13.8% of recoverable world hard coal deposits are located in Europe, as opposed to 28.6% of lignites. With the Soviet Union, which possesses 30.9% of the world deposits of this mineral (mainly located in Siberia), it makes up about 60% of the world's lignite deposits. The countries that are in possession of large lignite deposits, such as the GDR, the FRG, the Soviet Union, Czechoslovakia and Poland, are those mostly interested in new technologies progressing extraction and utilization of these resources.

Based on IIASA data [*Rogner, 1987*], we show an estimated forecast of coals energy consumption in Europe until the year 2030. The forecast is presented in Table 2.

Table 2. Primary Energy Consumption Forecast, Europe, 1980-2030 (Technical Evolution Scenario).

	Year						
Region	1980	1985	1990	2000	2010	2020	2030
Brown Coal and Lignite							
Western Europe (eJ)	2.51	3.03	3.59	4.18	4.79	4.92	5.10
Eastern Europe (eJ)	5.47	5.83	6.18	5.34	4.54	4.10	3.71
Total Europe (eJ)	7.98	8.86	9.77	9.52	9.33	9.02	8.81
Total Europe (million MTPY)[a]	886.70	984.00	1085.60	1057.80	1036.70	1002.20	978.90
Bituminous Coal and Anthracite							
Western Europe (eJ)	9.79	9.64	8.94	7.21	6.23	6.74	6.47
Eastern Europe (eJ)	4.47	4.76	4.75	5.67	6.79	6.59	5.93
Total Europe (eJ)	14.26	14.40	13.69	12.88	13.02	13.33	12.40
Total Europe (million MTPY)[b]	648.20	654.50	622.30	585.50	592.80	605.90	563.60

[a]Conversion factor = 9.0 GJ/T.
[b]Conversion factor = 22 GJ/T.
SOURCE: Rogner (1987).

It can be seen that increases in yearly lignite consumption in Europe in the year 2000 will be about 1.54 eJ* (171.1 million MT**), and in 2030 about 0.83 eJ (92.2 million MT) from the 1980 level. In 1980 the consumption level was 7.98 eJ (886.7 million MTPY***).

This forecast is of illustrative character to envision the problem scale. At the next research stage revisions are foreseen based also on technological analysis. The analysis should spread more light on the potential processing of lignite (demand side) helping to formulate and examine the forecast on extraction. Of course the forecasts on other energy carriers should be taken into account accordingly as it is explained in Section 2.3.

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*1 eJ = 10^{18} J.
**1 million = 10^{6} units.
***million MTPY = 10^{6} Metric Tons Per Year.

2.2. The Problem of Sulfur and SO_2

Assuming perhaps an overoptimistic level of burning sulfur content in raw lignite of 0.5% and burning processes without pollution control facilities, the above forecast would mean that with the present technology an increase of SO_2 emission by the year 2000 as compared to 1980 would be in the range of 1.7-1.8 million MTPY. This is absolutely not acceptable!

Unfortunately, the sulfur content of both coal and lignite deposits remains insufficiently known. Moreover, it is likely that the sulfur content in newly exploited deposits is greater as deposits with low sulfur content have become exhausted.

If the burning sulfur content in lignites extracted in Europe increases (to about 1 wt%) [*General Report of UNC, 1979*] in line with the consumption rates (increase by 171 million MTPY), then SO_2 emissions will rise by 3.42 million MTPY. Given the 1980 extraction of some 900 million MTPY and an optimistic sulfur content of 0.5%, the SO_2 emissions from the combustion of lignite will reach a level of some 12.3 million MTPY for Europe in the year 2000 (without air pollution control facilities).

Technological innovations ("transforming technologies" as we call them) can allow reductions in the emissions through increased efficiency of pollution control devices. Moreover, sulfur extracted from coal and lignite could be used as raw material for production instead of being a pollutant. Emergence of economically feasible technologies, which would enable the above, may prove to become a remedy for lack of complete data on the sulfur content of various fossil deposits. The new technologies may convert the problem of sulfur content from a rather touchy environmental into a profit based industrial processing issue.

New technologies of energochemical processing of lignite (such as the PYREG technology) could in an extreme case allow for a reduction in SO_2 emissions to 2.27 million MTPY at 1980 consumption levels. The increase of SO_2 forecasted for the year 2000 could be reduced to the level of 0.87 million MTPY if new technologies were totally adapted. Therefore, total SO_2 emissions could be decreased by 9.15 million Mt/y.

The above estimates are, of course, theoretical since the actual market penetration of new technologies will not reach 100% in such a short period of time. But it illustrates the theoretically attainable potential for reducing SO_x emissions. This is summarized in Table 3.

Table 3. Sulfur Dioxide Emissions in Europe With and Without PYREG (in million MTPY).

	1980	2000
Consumption of lignite	866.70	1057.60
Emission without PYREG	8.87	12.29
Emission with PYREG	2.27	3.14

What is even more interesting, the process would, at the same time, yield pure sulfur at the level of 3.94 million MTPY which could have a tremendous impact on the market.

A similar evaluation should be done for hard coal. For the sake of illustration let us consider the following case.

In the case of coal sulfurization the numbers are even more difficult to obtain. At this stage of consideration it seems to be sufficient to give only estimates that can be used for scaling the problem.

In the case of coal (high sulfur content, about 3% in raw coal) from combustion of 120 million MTPY of such coal, the emission of SO_2 would be in the range of 6.24 million MTPY. Highly sulfurized coals are often most easily accessible and therefore the cheapest in terms of production cost, whereas low sulfur coal deposits are mostly exhausted.

Applying the PYGAS technology, which will be discussed later, the SO_2 emissions could be reduced by a factor of 5.76. This would reduce SO_2 emissions from 6.24 to 1.08 million MTPY, yielding also 3.06 million MTPY of sulfur. If assuming perhaps a more realistic average sulfur content such as 1.5%, the above numbers would have to be divided by a factor of two. The above numbers are also of illustrative character as in the case of lignite discussed above.

The amount of 120 million MTPY of coal was taken for the illustration since it is roughly a level of coal combustion in Poland at present. That is not to conclude that the emission level for Poland is so extremely high, because no desulfurization plants are installed yet.

If the necessity to reduce SO_2 emissions would force purification of fossil fuels (coal and lignite), then important structural changes in energy systems might take place. One example of such an impact will be vast amounts of recovered sulfur. Before discussing the PYGAS and PYREG technologies, some of these impacts will be examined first. One of the methods of identification of those impacts on a rather general level will be the examination of crude oil and LPG processing industry and possible existing or potential interactions.

2.3. Interactions with Crude Oil and Gas Industries - Conflict or Complementarity?

A lot of studies and effort have been invested to understand the factors governing the market for crude oil and LPG, as well as related technological structures. It is almost trite to say that the modern world economy has come to be so decisively dependent on these resources. From this complexity we decided to tackle here only specific aspects related to the problem posed in the title of this section. A short bit of history is necessary for a start. The 1950s were on an unprecedented scale. A period of innovative development of the crude oil refining and petrochemical processing industries. The 1960s brought another acceleration, which is mainly expressed in the increase of scale of production and processing units. For example, typical installations for gasoline pyrolysis with a capacity of 60,000 MTPY went up to 500,000 MTPY. The 1970s brought the oil shocks together with technological maturity of the industry. The 1980s brought, as a result of the previous history, quick changes in the world situation of this industry. These changes can be characterized as follows:

- Geographical reallocation of the production capacity of basic chemical feedstocks such as ethylene (olefins) and its derivatives;
- Structural changes in feedstocks used for olefins production, and
- New developments in thermoplastics.

The first half of the 1980s can be summarized as a period of expensive raw materials (especially crude oil), expensive energy and expensive investments.

The growing capacities of olefins production (specifically ethylene) are moving to the countries producing crude oil. This was accompanied by a growing interest in the utilization of LPG which for years was wastefully burnt. According to UNIDO, even currently in 18 countries producing crude oil, an energy equivalent of 2.6 million barrels of crude oil per day is burnt. For example, Saudi Arabia increased its production and export of LPG from 5.39 million MTPY in 1979 to 10.92 million MTPY in 1982 and aims at 12.5 million MTPY in 1990. Algeria will become the second biggest exporter of LPG with exports of 1.6 million MTPY LPG (in 1984). The total world LPG production in 1981 was about 120.5 million MTPY and it is expected to rise up to 150 million MTPY in 1990.

These numbers illustrate the dynamics of the above phenomenon. To summarize the structural changes in the chemical feedstock industry, it can be estimated that in 1990 about 40% of the world olefin products will come from the gas pyrolysis technology which is relatively fast substituting a gasoline pyrolysis technology. For comparison, the structure of feedstock for ethylene production in 1981 is shown in Table 4. These structural changes must have important consequences. It can be estimated that the growing share of LPG (in global supply of chemical feedstock) due to its chemical nature could cause a decline in supplies of the important chemical feedstocks:

- Propylene 2.8 million MTPY;
- Butadiene 1.0 million MTPY; and
- BTX (benzene, toluene, xylene) 3.1 million MTPY.

Table 4. Structure of Feedstocks for Ethylene (Olefin) Production, Worldwide, 1981.

Source	Percentage
Natural gas and LPG	31
Gasoline	58
Fuel oils	11

SOURCE: Franik, 1984.

The above numbers are taken from unpublished forecasts by H. Franik [*1984*] and illustrate an absolute necessity of studying more deeply technological and structural changes of the above type. This is indispensable when trying to solve the problem of ESD for Europe with respect to coal and lignite.

The immediate proof of the above statement comes from the fact that coal and even more so the lignite processing yields an aromatic feedstock, which is the key feedstock for the organic chemistry. This shows that the energochemical processing of coal and lignite not only would lead to a decisive reduction of SO_x, but could match independently developing structural changes, which take place in supplies and processing of the petrochemical feedstocks.

Similarly, one should study the impacts of steel production decreases in Europe causing in turn reductions in the demand for coke, which may lead to a drop in the supply of important intermediates such as naphthalene and anthracene. Again, new developments in coal and lignite processing could compensate this loss.

The overview given above aims at formulating a thesis on how the problem of finding trajectories from the existing to the target (or NIES) structure should be attacked.

3. ENERGOCHEMICAL DEVELOPMENTS: THE CASE OF POLAND

3.1. The Scope

The close-up approach assumed in this study and outlined in the Introduction is taking us to "the case of Poland". This case is to be worked out along the lines following the assumed goal. The proposal of M. Zebrowski [*1985*], which was one of the origins of this study, was explicitly designed to investigate specific technologies which might be undertaken over the next decade in Poland (but definitely not exclusively). The aim is to investigate how adoption of the new technologies could effectively relax environmental constraints and expand economic opportunities for the sustainable development of the chemical and energy sectors, and so contribute to the national economic recovery.

The case of Poland could not be examined independently from continental trends in environmental change, about 30% of air pollution comes from abroad. At the same time, Poland represents a level at which strategic interventions can be made.

In this section we examine how Poland could try to reach Häfele's so-called Novel Integrated Energy Systems. We consider the feasibility of achieving such an energy system, how to sustain this system and will explore the implications of such a system for energy futures following exhaustion of conventional primary energy carriers.

However, this covers an extensive and wide field of research and can be done step by step only. In this paper only the first stage aimed mainly at identification issues and problem formulation is covered. It also has to be stated clearly that a lot more on the NIES concept is to be investigated. Some of these questions are posed in conclusions. A kind of feedback in terms of questions to NIES and the alternative trajectories worked out for Poland will be provided by the study discussed here.

3.2. Redevelopment Constraints of the Chemical and Energy Industries in Poland

While the scale of Polish economic difficulties is well known, it is worth outlining some of the critical contributing factors from the point of view of the chemical and energy industries that are the backbone of the economy.

The Polish economy is very energy consuming (see Table 5), which is to a large extent the result of conscious post-war economic policy. From the very beginning, post war Polish industrialization was characterized by a high energy consumption resulting from the emphasis on the development of heavy industries, such as iron and steel. This emphasis on heavy industries stems from the combination of a need to rebuild the economy completely devastated by the war and from the post war geopolitical history of Europe.

In striking contrast to other countries, even those with large coal deposits, Poland is characterized by a high dependence on coal and the underdevelopment of oil based chemical and energy sectors. Nearly 80% of the fuel and energy demand is satisfied by coal, and as much as 96% of electricity is generated from coal.

Poland never took advantage of the cheap crude oil of the 1950's and 1960's and, as a result, there was little development of a crude oil processing industry for energy and chemicals. Oil processing infrastructure remains limited, and prospects for an oil based recovery of the energy industry is minimal, even if cheap oil were to become available. The same applies to natural gas technologies.

Table 5. Energy Consumption per 1000 USD of GNP in 1980 (in tons of coal equivalent).

Region	Consumption
Poland	1.290
Austria	0.634
West Germany	0.616
France	0.573

SOURCE: *DOE Monthly Review*, May 1983.

Today, the long tradition of coal mining in Poland is stronger than ever. The coal industry provides one of the most important sources of export revenues, and sees itself as pivotal to any economic recovery in Poland. This attitude, prevalent both among economic planners and the public at large, has further prevented the development of an oil based energy and chemical sector. The continued economic reliance on coal exports has also limited domestic opportunities for a decreasing reliance on coal.

Since the end of World War II Poland has exported over one billion tons of coal and has every intention of continuing exports in the future. However, the mining industry has reached a situation in which the accessible high quality coal is exhausted. Geological conditions are such that the extraction of high quality coal is becoming increasingly difficult and costly. The remaining shallow coal deposits are characterized by a high sulfur content and so have largely remained unexploited.

Coal production has reached 200 million MTPY, and it is unlikely that it will rise much in the future. Over the years mining processes have also led to substantial ecological damage at an unprecedented scale. Salinization of the Odra and Vistula Rivers is a particular problem, e.g., the salt content of the Vistula River exceeds at some parts that of the Baltic Sea and almost never freezes in winter. In addition, the heavy dependence of energy production on coal has directly led to sulfur dioxide emissions exceeding 2.5 million MTPY and substantial NO_x emissions.

Newly built chemical plants are characterized by large production units. A relatively large heavy chemicals sector, highly dependent on energy from coal, has been developed. In other countries, the pressures of heating and motor fuel demand led directly to the growth and development of crude oil based energy and related chemical production. This dual pressure has been largely absent in Poland. Consequently, crude oil processing capacity remains underdeveloped relatively to the size of the national economy. At the same time, fortunately both among politicians and the public the consciousness of the environmental threat is taking high priority.

As a result, restructuring the energy and chemical sectors through imports of crude oil or gas is unlikely to succeed. Opportunities for importing new energy and chemical technology are likely to remain extremely restricted on account of the lack of funds. Large investment capital for restructuring the energy and chemical industry will also remain unavailable.

This situation works towards reconsideration of the traditional approach to coal and specifically its export. Should the coal production be more domestically oriented with decreasing emphasis on export, then apparently something has to be done with coal processing technologies - both energy and chemical.

3.3. Development Constraints of the Energy and Chemical Industries

Given the many constraints in restructuring the energy and chemical industries, it is worthwhile to consider a path to economic recovery that ensures an ecologically sustainable development. Such a path would:

- be based on coal, lignite and hydrocarbons, to be used in both the energy and chemical sectors. These would need to become one integrated sector since they utilize common natural resources. Conflicts between these sectors must be avoided;
- sustain innovation in energy technology dependent on the processing of primary energy materials (crude oil, gas, coal, lignite ...);
- in the long term the development of nuclear energy (e.g. breeder reactors) will foster innovations in the energy and chemical sectors, as nuclear power generation will release resources for development of energy and chemical processes - should not the recent events in the nuclear energy industry delay this option;
- avoid technological changes in coal based energy production, due to the existing scale of utilization of high capital intensive technology (conventional power stations);
- encourage innovations based on the existing domestic infrastructure of energy production;
- concentrate on the energy and chemical processing of lignite and coal; and
- minimize environmental damage and waste in natural resource exploitation.

In addition, any successful path to economic recovery must recognize that existing technologies of the energy production are perceived among both planners and the public as being well understood, stable and "publicly acceptable", despite a high consciousness of its ecological destructiveness. The strategic national importance of the energy and industrial sectors is deeply embedded in Polish culture and psyche. There is a prevalent and seemingly contradictory recognition that energy and chemical technology is vital to economic recovery. Such a situation may provide a climate which calls for a technological innovation capable of transforming the existing environmentally destructive and economically depressed industrial sector into one which is not only economically productive but ecologically sustainable.

Any further considerations are bound to be based on the investigation of relevant technologies. This should also include an evaluation of the potential structural penetration of new technologies into the chemical and energy sectors.

4. TECHNOLOGICAL INNOVATIONS FOR ENERGOCHEMICAL LIGNITE AND COAL UTILIZATION

4.1. Assumed Scope.

There is a substantial number of innovative technologies which were developed for coal and lignite processing. The so-called first and second energy crises have evidently accelerated their development.

However, due to the nature of technologies developed, the period, which we may call here a technology development cycle, is long, since it covers research and development, design, investment and market penetration of a given technology. An important development, such as the TEXACO coal gasification technology, started in the beginning of the 1940's [*Nietschke, 1986*] and took more than 40 years to achieve maturity.

We have decided to concentrate our interest on two technological innovations for energochemical lignite and coal processing namely PYREG and PYGAS respectively.

These two innovations are domestic, i.e. Polish, and they fit well the case under consideration. It does not mean at all that we drop the possibility of taking into account other technologies, such as the above mentioned TEXACO or e.g. those developed by Babcock [*Babcock Interim Report, 1986*]. Another interesting concept for the energochemical processing of coal and lignite is based on coupling the steam power generation (gas-steam turbine) with coal and lignite gasification processes [*Nietschke, 1986*]. This technology is in fact foreseen as an integral part of the NIES concept. It seems, however, that the other technologies should be taken into account at the next stage when the results of the present analysis could be used.

1.2. PYGAS Technology

Coal Pyrolysis in the Gas Stream (PYGAS)* is a technology which can potentially provide means for tracing a path to ecologically sustainable redevelopment through energo-chemical processing of coal and lignite.

The PYGAS process takes place in a hot gas stream which forms a heating medium, a polydispersive dust solvent and a transport medium. Coal of a grain size 0-200 μm** is fed into this gas stream. All grades of hard coal and lignite including caking coal and coal with very high sulfur content can be used in the process. The optimum temperature of pyrolysis (and pyritic coal de-sulfurization) is about 800 C, the time of pyrolysis is in the range of fractions of one second, the temperature of gaseous heating medium at the inlet to the mixing unit is 1500 - 1800 C.

Coal dust is fed into a cyclone combustion chamber with or without additional oxygen. Pyritic coal dust is added at a temperature of 350 C to the stream of hot gases from the combustion chamber (1500 - 1800 C). The process of pyrolysis and coal de-sulfurization takes place in a pipeline, resulting practically in the total removal of pyritic sulfur. After pyrolysis, the de-sulfurized char is separated from the pyrolysis products in a cyclone and is stored in a tank from where it is directly fed to conventional dust burners of a boiler. The pyrolysis gas can be used for energy generation or as a raw material for the chemical industry, after de-dusting and purification from H_2S and water. Full tar cracking enlarges the yield of the resulting pyrolysis gas.

Various versions of PYGAS are in existence. The two most prominent ones differ from each other by an oxygen gas stream in one and an air gas stream in the other.

PYGAS units are relatively simple and cheap to install in existing power plants, and are cost effective in their operation. It has been estimated that the cost of installing PYGAS will amount to no more than an additional 10% of investment costs of a conventional power station. The PYGAS process is characterized by a very high reactivity of char, allowing it to be burned in a conventional dust burner which is endemic to the Polish industry. Thus, there is an opportunity for adopting the PYGAS technology throughout the existing industry.

PYGAS may provide an opportunity for tracing an ecologically sustainable development path in situations where there is a high dependence on coal based energy production and limitations to large new investments. The technology can

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* Licensor: PROSYNCHEM Design Office, Gliwice, Poland. Patent No 87904.

**μm = 10^6 [m].

potentially lead to an increasingly efficient use of coal, while decreasing environmental impacts within constraints of the existing infrastructure of the energy and chemical sectors.

The idea behind the strategy of introducing PYGAS technology into the energy and chemical industries is backed by the fact that it meets all the constraints and the criteria that were formulated in Section 3. Specifically, the PYGAS technology can be introduced into a power station without significant alteration of the power plant. Since power plants are very capital intensive, it means that the PYGAS technology can be introduced as a means for modernization of existing power plants and thus help to avoid heavy investment. This will be seen even better in the case of lignite and the PYREG technology, which will be discussed later on in more details.

1.3. PYREG Technology

PYREG is a technology developed for lignite processing. Essentially it is derived from the PYGAS concept and is based on fast pyrolysis in a stream of recycled gases.

Research of PYREG is carried out by ICRI - the INDUSTRIAL CHEMISTRY RESEARCH INSTITUTE - in Warsaw, [*Rejewski et al., 1985*].

In fact, PYREG is a key element of the so-called energochemical complex. The case of lignite will be described in more detail because of its importance for the principal idea of this paper. Last but not least, the chemical and physical nature of lignite distinguishes positively this resource from coal.

The following guidelines were assumed for technological and economic properties of the lignite processing technology which resulted in PYREG:

- The process is to be as cheap as possible in terms of FCI (Fixed Capital Investment);
- Liquid and gas feedstocks for further processing are to be obtainable, the process must yield those feedstock together with solid fuel for conventional power units; and
- The technology must not be very sophisticated (in terms of hardware and operation).

The PYREG technology is currently at a large scale laboratory testing stage [*Rejewski et al., 1985*].

PYREG advantages in comparison to other methods of lignite pyrolysis can be summarized as follows:

1. Raw material for the process is a typical boiler fuel (powdered lignite) used in existing power stations. This enables simple and easy coupling of pyrolysis plant with power boiler facilities;
2. Semicoke obtained from pyrolysis can be fed directly to dust burners of a boiler (see PYGAS technology);
3. The de-sulfurization level is in the range of 40-60% (it is less than in the case of PYGAS for coal, but the burning sulfur content in lignite usually does not exceed 0.5%; at least in Poland),
4. Pyrolysis gas obtained from the process does not contain such impurities as N_2) that are difficult for separation; and
5. A high yield of crude tar is obtained (15-25 wt%, based on dry lignite feed) as compared to the traditional low temperature lignite pyrolysis – the Lurgi Spülgas process (10-12 wt%).

Due to the above properties, PYREG is an ideal process for implementing the concept of an energy-chemical site. The idea is presented in Figure 1.

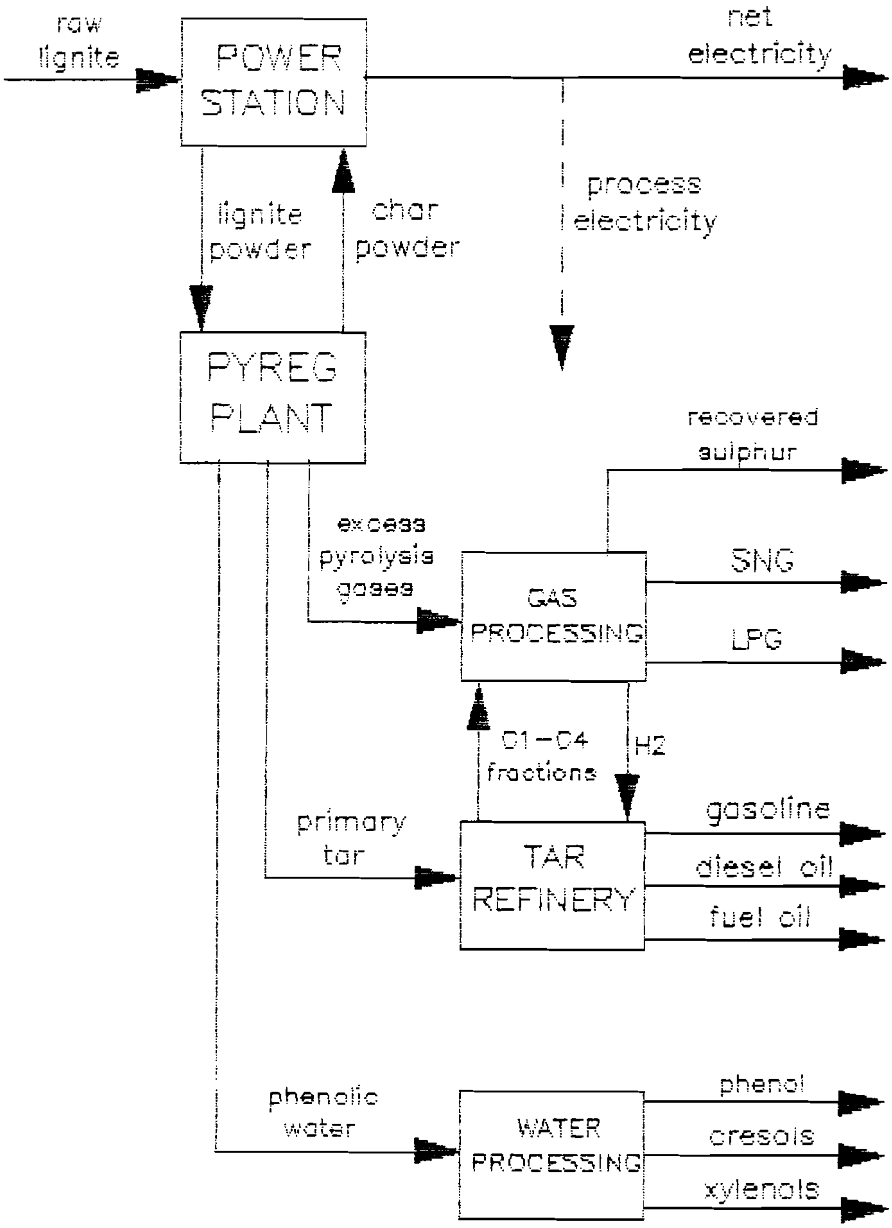

Figure 1. Basic Idea.

To illustrate the properties of the ENECHEM PYREG site (or short ENECHEM site), which in fact integrates chemical and energy industries, an example will be used.

Let us consider a surface lignite mine yielding about 18 million MTPY (burning sulfur content is about 0.5% in raw lignite). Such an output provides fuel sufficient for a power station of medium size (2160 MW - 6 blocks of 360 MW). The following were compared:

Energy Conversion Efficiency *ECE* based on net *LHV* Lower Heating Value *LHV*;

Fixed Capital Investment *FCI* calculated for the beginning of the 1980's;

Chemical production;

SO_2 emissions (assuming that S content in lignite is 1%).

To obtain an equivalent amount of fuels produced by the ENECHEM site, a modern type of crude oil refinery has to process 1.5 – 2.0 million MTPY of crude oil (the refinery must have a catalytic cracking plant). The yield of chemical intermediates from the ENECHEM site is an additional asset. Table 6 compares the ENECHEM site and a conventional power station . As can be seen from the table, the energochemical processing of lignite in the energochemical site at the cost of about 33% of the site, yields over 1.2 million MTPY of liquid fuels and about 130,000 MTPY of valuable chemicals. Moreover, about $400 \cdot 10^6$ scm/yr* of synthetic natural gas (SNG) is obtained, while reduction in SO_x emission yielding almost 67,000 MTPY of sulfur.

Table 6. Comparison of Conventional Power Stations and Energochemical Sites.

	Conventional Power Station	ENECHEM (energo-chemical site - PYREG)
Coal consumption	18 mln MTPY	18 mln MTPY
Power	6 X 360 = 2160 MW	4 X 360 = 1440 MW
ECE	35 %	57 %
FCI (1985 mln USD)		
Power station (860 USD/kW)	1 858 mln USD	1 238 mln USD
Chemical plant	-	600 mln USD
Total	1 858 mln USD	1 838 mln USD
Chemical products		
SNG (C1 - C2)	-	400 mln scm/yr
LPG (C3 - C4)	-	150 000 MTPY
Gasoline	-	430 000 MTPY
Motor oil	-	580 000 MTPY
Heating oil (less than 1% S)	-	75 000 MTPY
Phenol	-	13 000 MTPY
Crezols	-	27 000 MTPY
Xylenole	-	26 000 MTPY
Sulphur 99.5% (recovered)	-	67 000 MTPY
Sulphur dioxide emission	180 000 MTPY	46 000 MTPY

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*scm/yr = standard cubic meter per year.

1.4. PYREG and Waste Utilization

European lignite, especially in central Europe (the GDR, the FRG, Poland, and Hungary) is of earth-xylite type. The xylite content is 2-10% or an average 5%. In the case of conventional power stations they are wasted and cannot be utilized. In the case of the example discussed above, it means that 900,000 MTPY of this type of wastes have to be dumped.

The PYREG technology enables utilization of xylites in a separate block of PYREG for xylites. Such a unit can produce:

- 260 000 MTPY of higher grade fuels with LMV 28-30 GJPT;
- 65 000 MTPY of hydrocarbons, fatty acids, ketones; and
- 60 million scm/yr of chemical gas feedstock.

2. POSSIBLE INTEGRATION OF PYGAS AND PYREG INTO THE EXISTING INDUSTRIAL STRUCTURE

2.1. The Scope and the Goal

The term "possible integration into the existing industrial structure" must be somewhat explained. By giving two examples of possible industrial structure, which may emerge by implementing the innovative technologies, we would like to show wider technological impacts of the concept. This is a kind of analysis which is complementary to a macro analysis and fills the gap between this level and the enterprise level. Moreover, it cannot be left to the industry alone [*Dobrowolski et al., 1985*]. The material presented below gives results of a preliminary analysis based on real life cases modified only for obvious reasons - the proportions and relations remain practical and are not only an academic exercise. It is expected that this kind of analysis supported by various computer procedures being developed by JSRD can be assembled into a comprehensive and disciplined methodology [*Dobrowolski at al. 1985*]. This methodology could be used as one of the tools in devising policies with incentives for the industry. Incentives which would motivate industry towards a development coherent with the idea of ESD (see also Section 6).

2.2. Example of Industrial Structure with PYGAS

Figure 2 shows a schematic diagram of the existing industrial structure in a given region.

There are three separate enterprises:

- Carbon disulfide (CS_2) plants;
- Sulphur mines;
- Coal burning power stations; and
- Coal mines (with high sulfurized coal, about 3 wt%).

The only existing link is supply of sulfur for production of CS_2 – an important intermediate for artificial fibers and various synthesis. In order to avoid total disaster in agriculture, a power station cannot use highly sulfurized coal, which are located in this region. But supply of better coal is not always possible because it causes other problems and increases costs substantially.

Figure 3 shows the above system integrating the PYGAS technology.

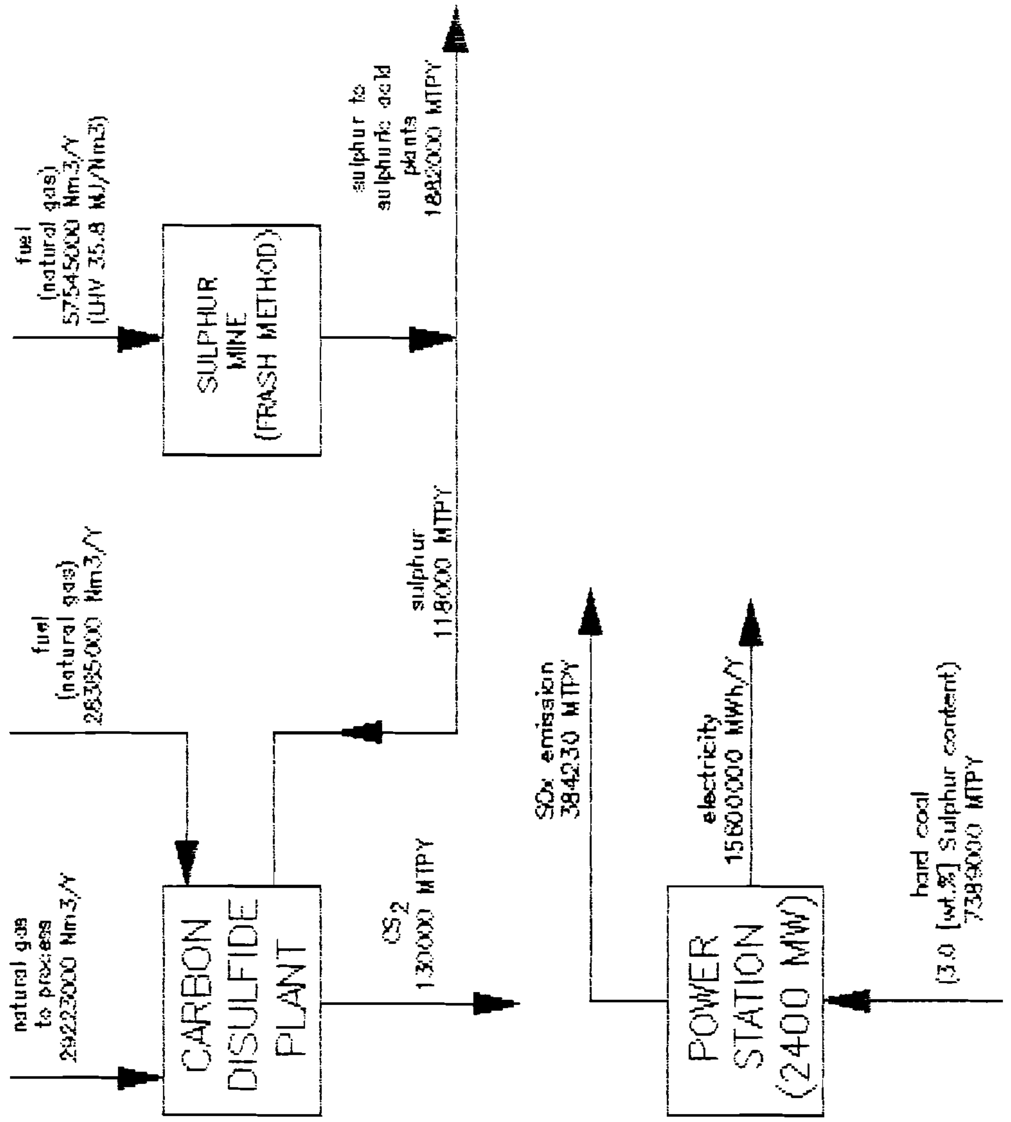

Figure 2. Existing Structure.

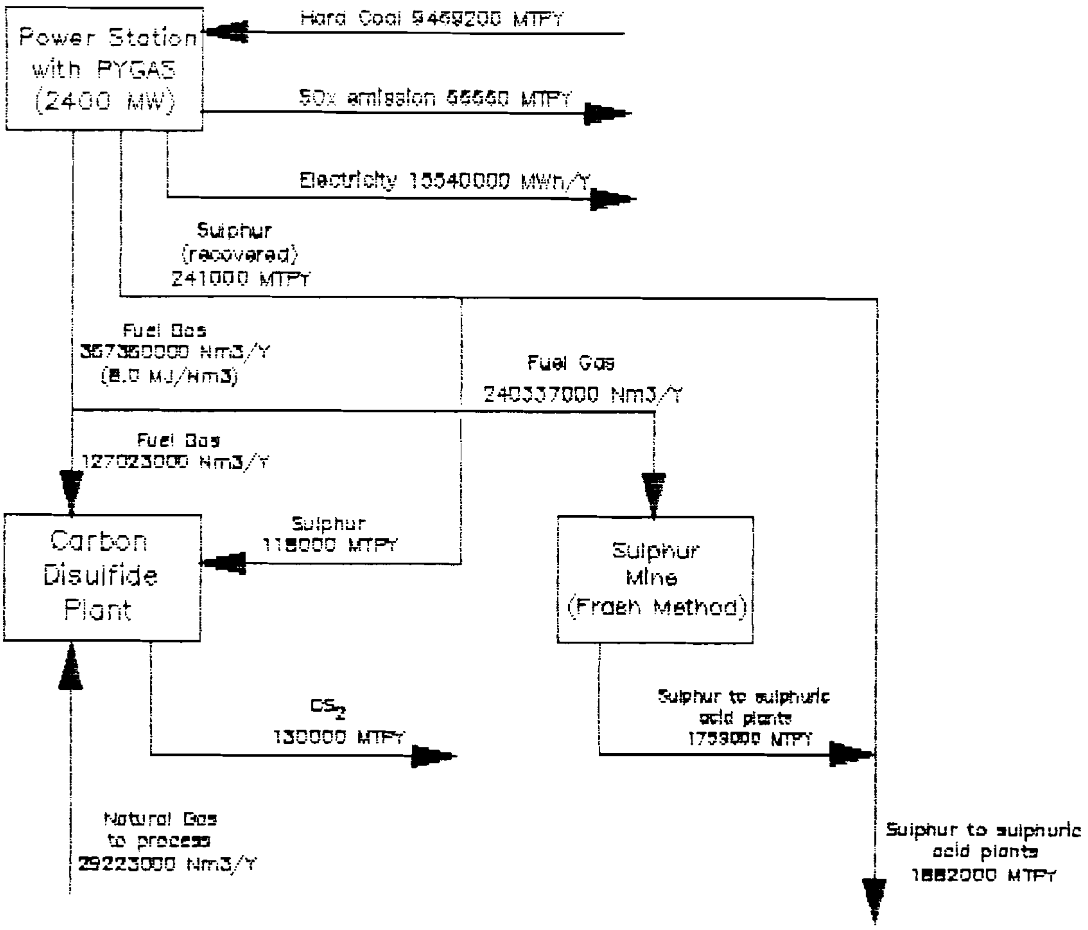

Figure 3. System integration of the PYGAS technology.

Table 7 summarizes the differences between existing and potential structures. The effects are very clear:

- Better utilization of resources (e.g. natural gas used only for technological purposes and not as a fuel);
- 5.8 times lower sulfur emissions; and
- Possible decrease in the production of sulfur with the Frash method.

2.3. Example of Industrial Structure with PYREG

Figure 4 shows a schematic diagram of the existing industrial structure in another region. There again are three separate enterprises:

- Chemical works producing mainly fertilizers and PVC;
- Oil refineries produce among other products also ethylene and motor oil; and
- Power stations coupled with a lignite mine.

Table 7. Comparison of Systems With and Without PYGAS.

	Input per Year	Output per Year
System 1: Carbon disulfide plant Sulphur mine Power station		
Natural gas	115 153 000 scm	
Bituminous coal (3% S)	7 389 000 MT	
Sulphur		1 888 200 MT
Carbon disulfide		130 000 MT
Electric power		15 600 000 MWh
Sulphur dioxide emission		384 230 MT
System 2: Carbon disulfide plant Sulphur mine Integrated power station with PYGAS		
Natural gas	29 233 000 scm	
Bituminous coal (3% S)	9 469 200 MT	
Sulphur (recovered and minded)		1 888 200 MT
Carbon disulfide		130 000 MT
Electric power		15 540 000 MWh
Sulphur dioxide emission		66 660 MT

The only existing link is supply of ethylene as a feedstock for PVC production. Figure 5 shows effects of possible integration of the above industry of the PYREG technology. Table 8 summarizes differences between existing and potential structures. Here effects also clearly differ:

- Possible saving of 1.5 million MTPY of imported crude oil;
- Saving of natural gas, used in high degree as a fuel for other purposes; and
- Additional supply of important chemical intermediates.

3. METHODOLOGICAL ISSUES

Devising a methodology for dealing with a problem area of such a complexity is a very difficult task in itself.

From the methodological point of view there are two layers which should be regarded:

- Identification of scenario alternatives; and
- Identification of technological alternatives.

When dealing with the above layers, the researcher should position himself as explorer and expert supporting a decision/policy maker who is to evaluate options and alternatives as they result from the identification process. The above assumptions are in fact basic for devising a methodology.

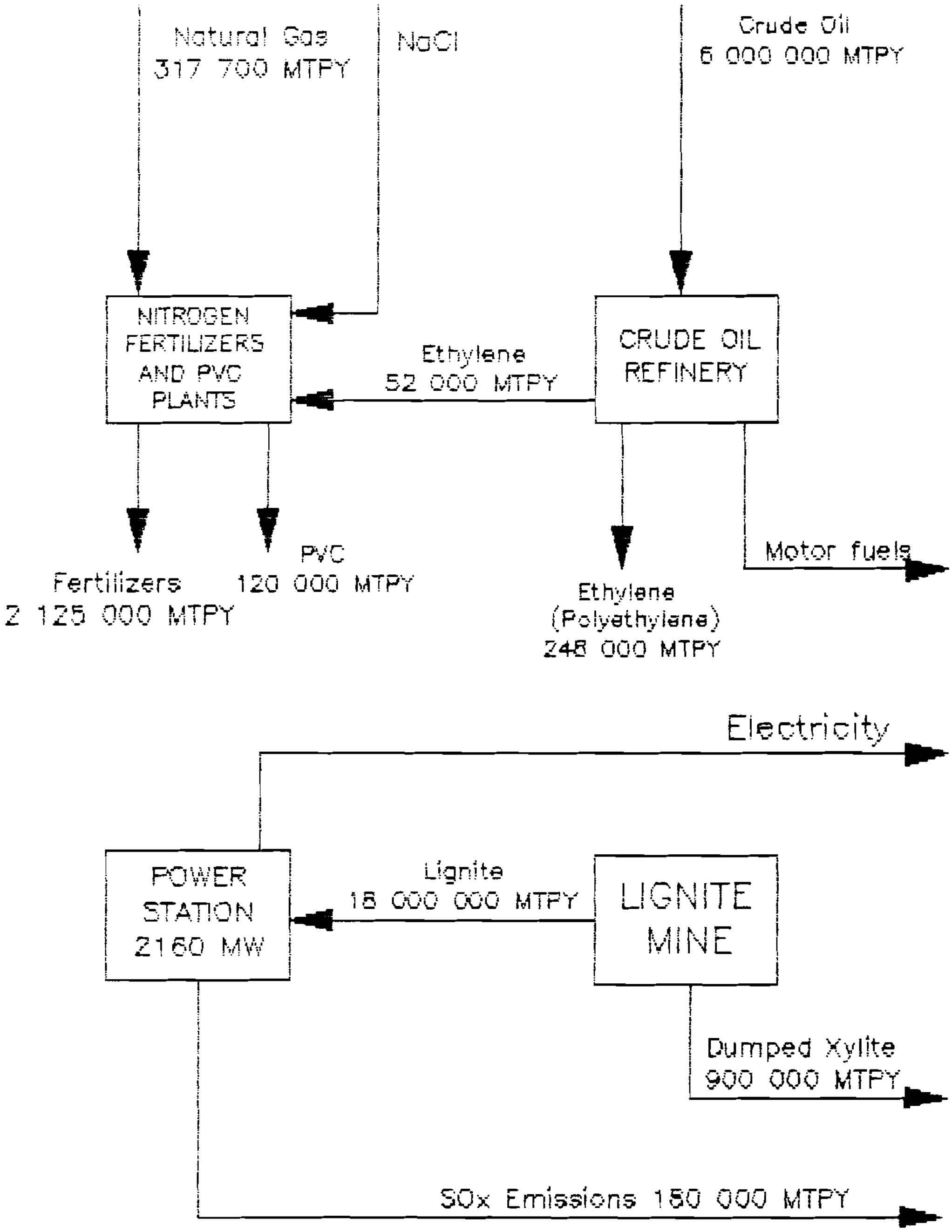

Figure 4. Existing structure.

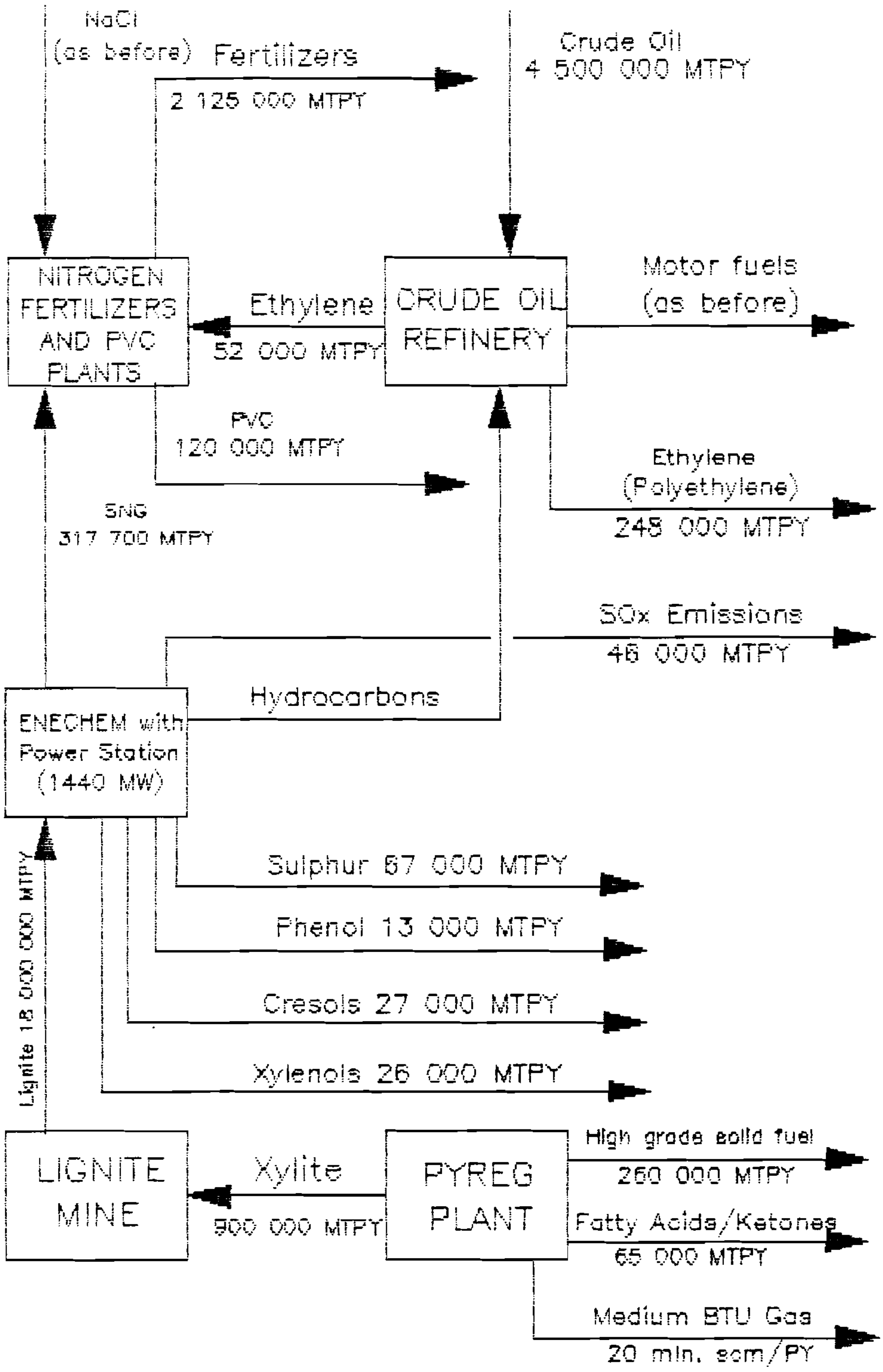

Figure 5. Systems integration with ENECHEM and additional plant for xylite processing.

Table 8. Comparison of Systems With and Without ENECHEM.

	Input per Year	Output per Year
1: N2 fertilizers + PVC plants refinery power station		
Natural gas	317 647 MT	
Crude oil	6 000 000 MT	
Lignite	18 000 000 MT	
N2 fertilizers		2 125 000 MT
PVC		120 000 MT
Motor fuels*		
Ethylene		300 000 MT **
Electric power		14 040 600 MWh
Sulphur dioxide emission		180 000 MT
Dumped xylite		900 000 MT
2: N2 fertilizers + PVC plants refinery ENECHEM site (with xylite processing)		
Crude oil	4 500 000 MT	
Lignite	18 000 000 MT	
SNG***		
NPK fertilizers		2 125 000 MT
PVC		120 000 MT
Motor fuels *		
Ethylene		300 000 MT **
Electric power		9 360 000 MWh
Sulphur		67 000 MT
Phenol		13 000 MT
Crezols		27 000 MT
Xylenoles		26 000 MT
High grade solid fuel (28-30 MJ/MT)		260 000 MT
Fatty acids, ketones, hydrocarbons		65 000 MT
Medium BTU gas		20 mln Nm 3
Sulphur dioxide emission		46 000 MT
Dumped xylite -		

*Net motor fuels output is the same in both systems and varies with specific production program of refinery.

**52 000 MT used as input for PVC plant yielding a net output of 248 000 MTPY.

***SNG produced from ENECHEM substitutes natural gas.

As it can be concluded from the above, we are aiming towards a methodology based on the DSS (Decision Support System) philosophy. From our experience in the design of industrial development structures we have developed an appropriate methodology, it seems that this could provide a good point of departure for developing a methodology for the case in question. MIDA stands for Multiobjective Interactive Decision Aid. Despite the fact that this sounds like a strongly computer oriented tool, its philosophy is much broader. MIDA is a system based on simulation models and all adjacent software [*Dobrowolski et al., 1985*]. The extreme case it could be applied without a computer model at all, if such a situation would arise.

MIDA is based on the concept of an intermediate economy. It is surprising that with the tremendous effort invested in macroeconomics and a lot of knowledge and methods available for the corporate level, especially when dealing with development, there is no real interface between these two spheres. We believe that such an interface is absolutely necessary when dealing with long term industrial or technological development. This interface could be naturally called an intermediate economy. In this area the problem of industrial development is to be considered and attacked from the point of view of developing a technology which is a driving force of industrial development.

When talking about technological development, one cannot consider a single technology. A whole repertoire of interrelated technologies should be investigated at once. In the chemical industry it is specially evident since along the way of processing feedstocks through intermediates to final products (whether it would be market commodities or chemicals used as feedstocks for other industries), all these processing technologies form an expanded network with dimensions rapidly growing as it proceeds towards the market.

It has to be realized that the dynamics of technology development represents a surprisingly long time span included in the cycles: research, design, investment and market penetration.

The above brief characteristics shows the meaning and weight of the term intermediate economy. For that area the MIDA methodology was developed.

The basic tool for the MIDA methodology is a model of the so-called Production-Distribution Area (*PDA*) [*Dobrowolski et al.*, *1985*]. In short, it enables the modeling a technological repertoire of assumed scopes containing existing as well as potentially available technologies.

The simulation experiments serve the purpose of finding those industrial structures which fit best the assumed development scenario, thus representing an alternative to the Industrial Development Strategy (*IDS*). The scenario comprises various constraints in terms of resources, environment, etc. The case can be also considered as a dynamic trajectory [*Skocz and Zebrowski, 1986*]. Ranking and selection of alternatives obtained from various experiments is provided and group expertise (selection committee) can be applied for the process [*Dobrowolski and Zebrowski, 1986*].

Here we do not intend to describe in more details the methodological approach, since it has been described in various papers of our group (see references). It is foreseen that at the next stage, when appropriate models are built and applied, the methodology will be described adequately. This seems to be especially feasible due to the fact that MIDA is based on case oriented philosophy and its tools are to be assembled accordingly.

4. CONCLUSIONS AND PROSPECTS

The paper presents results of the first stage of studies in "Technological Innovations for Ecologically Sustainable Development"

The concept of the so-called NIES or Novel Integrated Energy Systems is assumed as an idea of a future energy systems [*Häfele et al., 1986*]. To achieve this and to provide practically applicable development alternatives a number of case studies must be carried out.

Specifically, according to Häfele's concept certain issues are still to be clarified such as e.g. the cost of new technologies. Unfortunately it can be expected that, since the basic processes are characterized by a high FCI*, the total NIES FCI may be high also. Another problem will be posed by construction materials

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*FCI = Fixed Capital Investment.

which (mainly special alloys), as in the case of inconel 726, containing over 70 wt% of chromium, may serve the purpose, but there might be a problem of its availability in sufficient quantities, not to mention strategic impacts it may have on the market (strong rise in demand for high chromium alloys).

A number of "in-depth" studies is required to fill the gap between the present system and NIES. Some of the questions and doubts can be formulated even now, e.g. gasification is one of the key processes in NIES that would produce carbon dioxide as well as conversion process for obtaining hydrogen. Another source of CO_2 will come from gas turbines. NIES' balance of CO_2 based on the stoichiometry is, of course, the ideal case. The amount of CO_2 emissions from real industrial plants may be higher. The problem of CO_2, known as the Greenhouse effect, causes the high demand of careful evaluations of CO_2 balance in any concept of Integrated Energy Systems.

The analysis of the PYGAS and PYREG technological innovations as well as their structural impacts prove to be very promising and should be continued. They also seem to be a very good vehicle for integrating the chemical and energy sectors. The integration appears to be inevitable. This is due to the nature of processing of primary energy carriers into consumable energy (electricity, fuels) and the fact that they are at the same time important chemical feedstock. Moreover the ecological impacts of both energy and chemical industries can be fought with only through purification of their feedstock. That can be accomplished through energo-chemical sites. In addition the integration in wider context proves to be also very promising and enables the amplification of positive economical and ecological effects. The case also illustrates progress which can be stimulated by application of system engineering.

The proposed study of so called Polish case helps to integrate regional or national case studies into the continental scale of ESD. In the above context the global overviews and impacts from other industries such as oil and gas must be permanently studied as well as possible complementarities and conflicts which may arise. Moreover also other possible interactions with other industries are to be perceived, specifically with steel industry.

The case of potential BTX supplies from coal and lignite processing filling the gap which may arise from structural changes in the petrochemical industry could serve as one of the examples.

On the other hand a conflicting situation may also take place due to potential supplies of phenols from PYREG technologies which may lead to overproduction.

One important task will be to acquire true and reliable data such as the sulfur content in European coal and lignite deposits so as to enable better assessment of the potential impact of the new technologies.

Sulphur recovery through purification of solid fuels is expected to become a major source of supply of this important raw material. For the Polish economy it may cause very severe consequences by cutting down a vital source of export revenues. On the other hand decrease in sulfur production through mining may have a very positive ecological effect and bring energy savings.

It is expected that at the next stages a more formal methodology will have to be applied, specifically the one based on modeling of the industrial structures such as MIDA methodology [*Dobrowolski et al.,1985; Skocz, Ziembla, and Zebrowski, 1986*]. Further extensions of MIDA are expected to be perceived towards ranking and selection of development alternatives [*Dobrowolski and Zebrowski, 1986*], since this is a crucial point in evaluation of various trajectories of development.

Last but not least one may ask why not to leave most of the tasks related to technological type of analysis to the industry? They are the best. The answer is simple. The industrial development brought as a result an impressive progress to the human civilization but also may bring ecological disaster if societies do not find appropriate means to control it and the way to this leads through understanding.

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