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# Multi-criteria evaluation of natural gas resources

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**Abstract**

Geologically estimated natural gas resources are 500 Tcm. With the advance in geological science increase of estimated resources is expected. Natural gas reserves in 2000 have been proved to be around 165 Tcm. As it is known the reserves are subject to two constraints, namely: capital invested in the exploration and drilling technologies used to discover new reserves. The natural gas scarcity factor, i.e. ratio between available reserves and natural gas consumption, is around 300 years for the last 50 years. The new discovery of natural gas reserves has given rise to a new energy strategy based on natural gas.

Natural gas utilization is constantly increasing in the last 50 years. With new technologies for deep drilling, we have come to know that there are enormous gas resources available at relatively low price. These new discoveries together with high demand for the environment saving have introduced a new energy strategy on the world scale.

This paper presents an evaluation of the potential natural gas utilization in energy sector. As the criteria in this analysis resource, economic, environmental, social and technological indicators are used. Among the potential options of gas utilization following systems are considered: Gas turbine power plant, combine cycle plant, CHP power plant, steam turbine gas-fired power plant, fuel cells power plant. Multi-criteria method was used for the assessment of potential options with priority given to the Resource, Economic and Social Indicators.

Results obtained are presented in graphical form representing priority list of potential options under specific constraints in the priority of natural gas utilization strategy in energy sector.


*Keywords:* Natural gas combine cycle; Phosphate alkali fuel cell; Multi-criteria analysis

## 1. Introduction

There is an abundance of natural gas in the world, but it is a nonrenewable resource, the formation of which takes thousands and possibly millions of years. Therefore, understanding the availability of our supply of natural gas is important as we increase our use of this fossil fuel.

As natural gas is essentially irreplaceable (at least with current technology), it is important to have an idea of how much natural gas is left in the ground for us to use. However, this becomes complicated by the fact that no one really knows exactly how much natural gas exists until it is extracted. Measuring natural gas in the ground is no easy job, and it involves a great deal of inference and estimation. With new technologies, these estimates are becoming more and more reliable; however, they are still subject to revision.

A common misconception about natural gas is that we are running out, and quickly. However, this is far from truth. Many people believe that price spikes, such as were seen in the 1970's, and more recently in the winter of 2000, indicate that we are running out of natural gas. The two aforementioned periods of high prices were not caused by waning natural gas resources—rather, there were other forces at work in the marketplace. In fact, there is a vast amount of natural gas estimated to be still in the ground. In order to understand exactly what these estimates mean, and their importance, it is useful first to learn a bit of industry terminology for different types of estimates.

As we enter the new millennium, humanity is facing a unique and far-reaching challenge. Our energy needs are growing as a result of continued population increases, economic growth and individual energy consumption.

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At the same time, emissions from fossil fuels, the main energy source for heating our homes and powering our economies, are contributing to climate change and affecting local air quality.

Alternative energy technologies offer one promising solution, although it will be some time before they become cost effective and widely available. Energy conservation is also a logical part of the solution, but even the most stringent conservation methods will not eliminate our need for energy. Other viable options are clearly needed.

The increased use of natural gas offers reduced emissions and significant environmental benefits now—locally, regionally and globally—and fulfils an important energy transition role as we look towards the future.

As the global community moves towards a less carbon-intensive energy future, it is important to recognize that natural gas occupies a unique and strategic position in the hierarchy of energy resource options.

Unlike coal and oil, natural gas has a higher hydrogen/carbon ratio and emits less carbon dioxide for a given quantity of energy consumed. However, to fully understand the greenhouse gas profile of any fuel source, it is important to look at its total lifecycle: all of the emissions associated with the fuel, including emissions from initial extraction, processing and delivery as well as those from its final combustion.

In the natural gas industry, greenhouse gases are emitted as a result of:

- processing and compression of the gas,
- fugitive emissions (unintended losses of gas during transportation and distribution),
- blowdowns (the deliberate release of gas during maintenance operations),
- combustion of natural gas during day-to-day operations (i.e. for vehicle use, heating).

Once natural gas is delivered to end users, greenhouse gas emissions are created during combustion.

## 2. Natural gas availability

### 2.1. Natural gas resources

The essential indicators for assessment of natural gas availability are resource and reserves indicators. For this reason it is of great interest to validate its availability and define the resource indicator as important parameters for evaluation of utilization of natural gas. As other energy resources, natural gas available resources strongly depend on two parameters: capital invested in geological survey and knowledge about geological structure. Also the energy reserves are subject to the following constraints: capital invested in drilling, technology advancement in deep drilling and offshore technology. It is known that total cost of drilling is about 20 $/oil equivalent. The investment in new reserves is subject to the energy strategy in the world and market driven forces. Fig. 1 taken from Coal and Natural Gas Electric Power System (2004) shows present estimate of the world natural gas reserves and resources and its geographical distribution.

In order to validate existing natural gas reserves in the frame of it potential exhaustion, it is of interest to observe past and present natural gas consumption. Fig. 2 shows the world natural gas consumption in 1981–2025 (International Energy Agency 2002, 2004). Constant increase of the natural gas consumption can be noticed.

The environmental benefits provided by natural gas and advances in technology are ensuring its role as the preferred fuel. There has been a steady increase in natural gas production over the past 10 years. Data reported by WEC Member Committees for the present Survey (Summary of Energy Resources, 2001), supplemented by information derived from other sources, indicate that world production of dry marketable natural gas was some 2.4 trillion cubic meters in 1999, an increase of 4.1% over the comparable 1996 total published in the 1998 Survey. Trends indicate that this steady increase will continue in the coming years as the world moves towards less carbon-intensive energy strategies. Early indications point to accelerated growth during 2000, reflecting the implementation of new and expanded LNG export schemes in Nigeria, Oman, Qatar and Trinidad (Fig. 3).

China's consumption of coal in 1999 decreased; at the same time it increased its natural gas consumption by

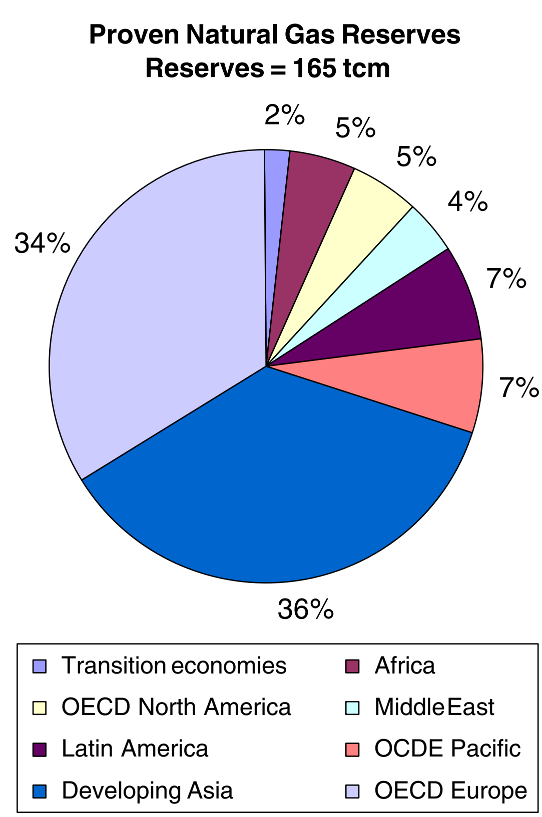


Fig. 1. Natural gas reserves.

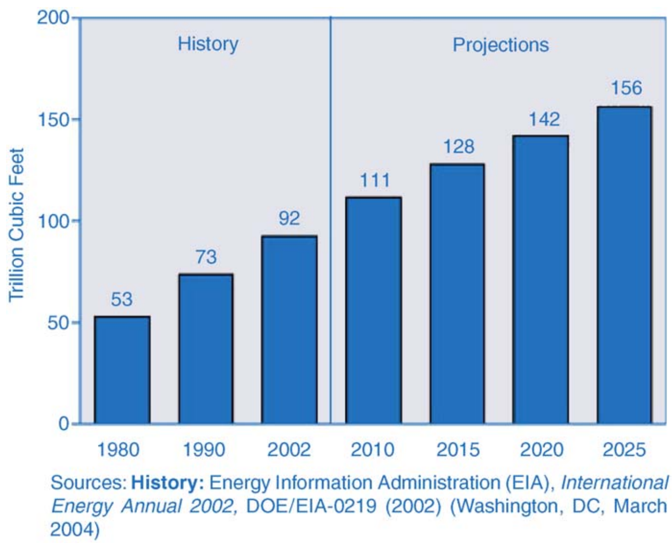


Fig. 2. World natural gas consumption.

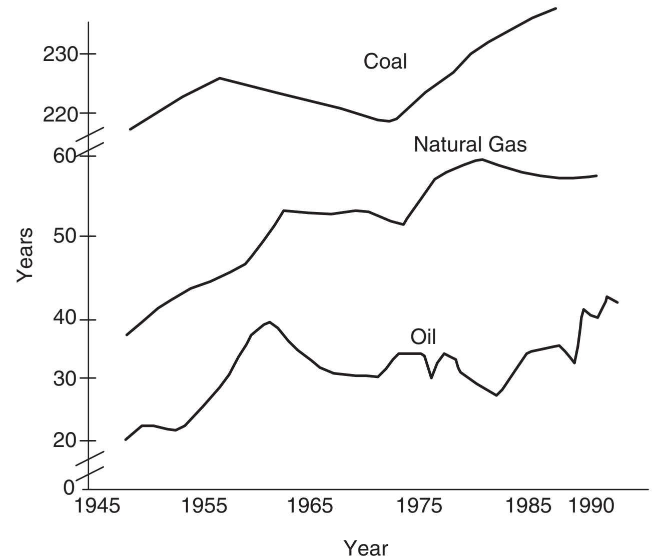


Fig. 4. Number of years for available reserves.

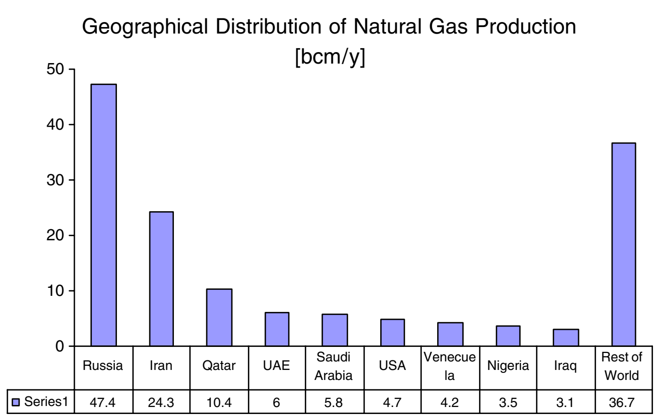


Fig. 3. Geographical distribution of natural gas production.

10.9% over 1998. In the Asia Pacific region, consumption of natural gas increased by 6.5%. With nearly 50% of the world's population, and growing economies that demand energy, this region has the potential to significantly affect the future demand curve for all energy sources.

It is anticipated that a fairly significant portion of the demand will be met by natural gas.

Viewed regionally, the African continent had the fastest rate of growth in consumption, with an increase of 9.1% in 1999. Africa has a growing potential not only as a market for natural gas, but also as a producer.

There are different methods of estimating the resource indicator in evaluation of the energy system using natural gas resources. Most frequently used indicator is scarcity factor which is defined over number of years before available reserves will be exhausted. Fig. 4 shows estimated changes in the number of years for the last 50 years for coal, oil and natural gas (Comparison of Air Pollution from Combustion of Fossil Fuel, 2004).

In the evaluation of natural gas use in energy system, as the resource indicator, natural gas consumption per unit kWh is used.

### 2.2. Environmental aspect of natural gas

Despite lifecycle emissions, however, natural gas compares very favourably against oil and coal. Taking a range of global warming potentials, even under the most conservative conditions of analysis (a 50-year timeframe), oil contributes 20% more $CO_2$ equivalent emissions than natural gas, and coal contributes 50% more. Additional analysis suggests that even on a conservative analytical basis, using natural gas in place of other fossil fuels is an effective way of reducing the world's greenhouse gas emissions and still meeting our energy needs.

As the cleanest burning fossil fuel, natural gas offers an immediate, cost-effective means to improve air quality. Unlike coal and oil, it releases virtually no particulate matter, which impedes photosynthesis in plants and aggravates heart and lung disease in humans. Particulate matter is also a contributor to smog (Table 1).

In stressed urban air sheds, where most natural gas is consumed for residential and industrial purposes, combustion of natural gas can have a positive impact on local air quality because it creates fewer air emissions Nonetheless, addressing the issue of air quality has become a priority concern for the natural gas industry.

In the evaluation of the environmental aspect of the energy systems with natural gas the unit production of gas product per unit kWh is used. Since $CO_2$ contributes to the adverse effect on environment, it is used to introduce CO/kWh as the Environment Indicator in energy system evaluation. In this respect priority has to be given to the lower Environment Indicator.

Table 1
Comparison of air pollution from the combustion of fossil fuels (Medows et al., 1972, in kilograms of emission per TJ of energy consumed)

| | Natural Gas | Oil | Coal |
|---|---|---|---|
| Nitrogen oxides | 43 | 142 | 359 |
| Sulphur dioxide | 0.3 | 430 | 731 |
| Particulates | 2 | 36 | 1333 |

### 2.3. Technology transfer

The transfer of technology from industrialized nations to developing countries will play an important role in balancing increasing consumption with the need for reducing emissions from fossil fuels. As a relatively abundant, economically feasible and cleaner fossil fuel, natural gas has many benefits for developing countries, especially as population migration from rural areas to urban centres puts increasing loads on urban air sheds. Foreign capital investment will be essential for developing the appropriate infrastructure, where required, and for expanding existing infrastructures. This indicator can be numerically justified by the amount of capital devoted to the development of specific energy system. Also, this indicator can comprise the assessment of maturity of the energy system under consideration. For the natural gas fired energy system this will imply the advancement expected in meeting the specific target.

There are four potential routes for future natural gas utilization for energy production:

1. combined cycle gas turbine system,
2. heat and power cogeneration,
3. fuel cells,
4. hydrogen production.

Potential future development of energy system for natural gas utilization will imply extensive development program with emphasis on the improvement of their economic performance, environmental acceptance and social adaptability. In order to validate each of these requirements the multi-criteria analysis is needed.

In order to measure technological criteria following indicators are defined: amount of capital to be used for the future development program, number of new job to be opened with new development of the respective system and new market opening.

### 2.4. Social aspect of natural gas

One of the important aspects of modern energy system is their social acceptance. It is becoming important in their design to adapt social constraint imposed on the specific energy system. For the natural gas system it is of great importance to justify social acceptance of the system and introduce those indicators for the assessment of natural gas energy systems. There are two main parameters which are relevant for the assessment of social aspect of energy system. One, reflects new job opportunity anticipated in the gas utilization route and the second is the new capital investment which will promote new development and increase taxation for infrastructure.

## 3. Selection of options and indicators for natural gas systems

### 3.1. Option selection

The selection of criteria and indicators depend on the system. Usually, it is anticipated that the system in an entity is to be defined with respect to the number of parameters describing the state of the system.

In this exercise we focus our attention on the gas turbine systems (Peter, private commun.). In this light we select number of options to be taken into a consideration, due so with the number of indicators of importance for assessment of the system. In selecting appropriate options for consideration following systems will be used:

1. Natural gas turbine system (NGTS)
For comparison with hydrogen fuel cell plant we choose the simple natural gas turbine energy system. Gas turbine energy system fueled with natural gas is one of the options to be taken into consideration in this evaluation. In order to compare with other systems, the simple gas turbine system is used to dodge the advantages of additional complexity of the energy system. Under this constraint total efficiency of the system $\eta = 0.36$ with inlet temperature $850\,^{\circ}$ C.
2. Natural gas combined cycle (NGCC)
Due to favourable condition with gas resources, recently it has become interesting to investigate the natural gas combine cycle power plant as a potential option in power generation (Kordische and Simander, 1996). With the present design of gas turbine efficiency of natural gas combined cycle (NGCC) cycle has become very attractive in many respects. Since efficiency of gas turbine cycle is very high, in the combination with heat recovery cycle and with steam turbine, it can reach an efficiency of 65%. With other advantages like easy control, $NO_x$ control and limited air pollution, NGCC has become one of the most promising options in the future strategy of energy system development.
3. Integrated gasification combined cycle (IGCC)
Integrated gasification combined cycle (IGCC) combines both steam and gas turbines (Pruschek, 1998). Depending on the level of integration of various processes, GCC may achieve 40–42% efficiency. The fuel gas leaving the gasifier must be cleaned (to very high levels of removal efficiencies) of sulphur compounds and particulates. Cleanup can be carried out after the gas has been cooled, which reduces overall plant efficiency and increases capital costs, or under high pressure and temperature (hot-gas cleanup), which has

higher efficiency. However, hot-gas cleanup technologies are in the early demonstration stage. After the fuel gas has been cleaned, it is burned and expands in a gas turbine. Steam is generated and superheated in both the gasifier and the heat recovery unit downstream of gas turbine. The fuel gas is then directed through a steam turbine to produce electricity.

4. Natural gas combined heat and power system (NGCHP)
   Recent advances in electricity-efficient, cost-effective generation technologies (in particular advanced combustion turbines and reciprocating engines), have allowed for new configurations of systems that combine heat and power production, expanding opportunities for these systems and increasing the amount of electricity they can produce (The Future of CHP in the European Market, xxxx). Many of these CHP systems place the electricity generation equipment, the turbine or engine, first in the system, using a waste heat recovery boiler to capture the heat. The captured heat can then be used to satisfy heating requirements, provide cooling using advanced absorption cooling technology, and even generate more electricity with a steam turbine.
5. Phosphoric acid fuel cells (PAFC)
   Phosphoric acid fuel cells PAFCs have been in 'commercial' production for more than five years, with about two hundred 200 kW units installed or in production (Kordische and Simander, 1996). These have historically been expensive, \$3000/kW, though assistance for purchasers has come through US Government programs. The price, even at that stage, was subsidized internally, and the current market price is \$3750/kW. This may seem an increase, but for the first time actually covers all costs of production.
   The PAFC represents the first generation of 'commercial' fuel cells. Although successful in terms of technical performance, questions lurk with regard to its cost reduction potential and whether may be a more competitive option in the future.
   All options taken into a consideration are $P = 100$ MW unit with natural gas with standard properties.

### 3.2. Indicators selection

Among indicators (The Future of CHP in the European Market, xxxx) to be used in this exercise are:

1. Resource indicator (RI)

In general terms, we can use respective indicators to measure dematerialization of the power plant. These indicators are defined as reference indicators, meaning use of respective resources for performance of the system. In this case, natural gas will be the fuel. So, Resource Indicator for assessment of different options of gas power plant under consideration is the fuel resource consumption indicator comprising of the amount of fuel per unit power produced.

In order to have the possibility of assessing the resource use of the different options under consideration, the cost of natural gas was selected as the parameter for the resource indicator. This indicator yields us the possibility to see contribution of the fuel cost to the total assessment of the system.

2. Economic Indicator (EI)

Since every system under consideration is subject to different efficiency it is of interest to have electricity cost as the integral parameter for the internal parameter of the system which comprises different design characteristics of the system. As the Economic Indicator in this assessment procedure, the electricity cost is used. This parameter comprises the total energy cost of production in the option. As it is common, this parameter for system evaluation is composed of capital, fuel and operation cost. Also, electricity cost reflects effect of thermal characteristics on general feature of natural gas system. Close link between internal parameters of the system and its performance makes assessment of size of the system flasible.

3. Environment Indicator ($CO_2$)

Present strategy in power plant design is strongly related to the modern approach in fuel gas emission control. Due to the global effect of $CO_2$ , its monitoring has become of paramount interest in the design of new gas power plant. For this reason, any design of power plant has to incorporate those features which are related to decrease of $CO_2$ emission per unit energy produced. Among the gas combustion products, $CO_2$ is the most important parameter for assessment of the natural gas systems effect on environment.

4. Social Indicator (LM)

The Social Indicators reflect the social aspects of the options under consideration. The job indicator represents the number of new jobs to be thrown open per unit MW in the option considered.

## 4. Multi-criteria analysis

Energy system is a complex system with a complex structure and can be defined with different boundaries depending on the problem. In the simple analysis in which the only function system is converting resources into the final energy, the interaction of energy system is defined by its thermodynamic efficiency. Adding some complexity to the energy system, we can follow interaction of energy system and environment. In this respect a good example is the pollution problem, which is defined as the emission of energy and material species resulting from conversion process. With further increase in complexity of the energy system and establishing respective links through the boundary, there are other fluxes between the system and the surrounding. Since every energy system has its social function in our life, it may also be established as a link between the energy system and the surrounding taking into a social interaction between system environments.

Table 2
Natural gas systems indicators

| | Resource indicator (c/kWh) | Economic indicator (c/kWh) | Environment Indicator (gr/kWh) | Social Indicator (Job/MW) |
|---|---|---|---|---|
| NGT | 1.42 | 0.035 | 97 | 3.0 |
| NGCC | 1.29 | 0.041 | 210 | 4.5 |
| IGCC | 1.53 | 0.034 | 90 | 4.3 |
| NGCHP | 0.82 | 0.0195 | 110 | 5.0 |
| PAFC | 0.65 | 0.042 | 450 | 4.0 |

In our exercise, we have assumed that the energy system is a complex system which may interact with its surrounding by utilization of resources, exchanging conversion system products, utilizing economic benefits from conversion process and absorbing social consequences of conversion process. Each of these interaction fluxes is a result of very complex interaction of elements of energy system within the system and also interaction with the surrounding. In our analysis we use synthesized parameters of the system in the form defined in classical analysis of energy systems. So, we use for resources utilization the Resource Indicators and for conversion process effect the $CO_2$ exhaust gas. The electric energy cost will be used to measure economic benefits of energy system and $NO_x$ release of the energy system will be used as the Social Indicator of the energy system

It can be noticed that data collection on earth resources, environment pollution parameters, economic system parameters and social structure and quality, is the first step in generation of indicators. The second step is definition of the energy system concept including the definition of structure and interaction between elements and processes. This will imply selection of energy conversion process and its interaction with inlet parameters.

The multi-criteria assessment is based on the decision-making procedure reflecting combined effect of all criteria under consideration and is expressed in the form of General Index of Sustainability (Morse et al., 2000; Afgan and Carvalho, 2000, 2005; Afgan et al., 2000; Hammond, 2000). Selected number of indicators are taken as measure of the criteria comprising specific information of the options under consideration. The procedure is aimed to express options property by the respective set of indicators.

### *4.1. Sustainability Index definition*

The decision-making procedure comprises several steps to obtain mathematical tool for the assessment of the rating among the options under consideration (Hovanov, 1996; Hovanov et al., 1997,1999). In order to prepare data for the NGS assessment the Table 2 presents the data to be used in the analysis.

General indices method involves formation of an aggregative function with the weighted arithmetic mean as the synthesizing function:

$$Q(q; w) = \sum_{i=1}^{m} w_i q_i,$$

where

$w_i$ is the weight coefficient elements of vector $\mathbf{w}$ and $q_i$ the indicators of specific criteria.

In order to define weight-coefficient vector, randomization of uncertainty is introduced. Randomization produces stochasticity with realizations from corresponding sets of functions and a random weight vector. It is assumed that the measurement of weight coefficients is accurate to within steps $h = 1/n$, where $n$ is a positive integer. In this case the infinite set of all possible vectors may be approximated by the finite set $W(m,n)$ of all possible weight vectors with discrete components. In our case, we will use $m = 4$, and $n = 40$ so that the total number of elements of the set $W(m, n)\, N(m, n) = 92251$.

For nonnumeric, inexact and incomplete information, $I = \text{OI U II}$ and is used for the reduction of the set $W(m,n)$ of all possible vectors $\mathbf{w}$ to obtain the discrete components set $W(I;n,m)$ is defined as to number of constraints reflecting nonnumeric information about the mutual relation among the criteria under consideration.

## 5. Multi-criteria natural gas system evaluation

Multi-criteria analysis is based on determination of General Index of Sustainability for all options under predefined constraint. In this evaluation the following cases are taken into consideration. The first case is aimed at investigating the situation where the weighting coefficients of all indicators are the same. The second case is designed to reflecting priority of the Resource Indicator, and the same values for the weight coefficient for other indicators. The third case is designed to give priority to the Economic Indicator and the same weight co efficient to other indicators third. The fourth case is to give priority to the Environment Indicator and imposes exaggerated diversity in the priority list. The Fifth case is reflecting situation where priority is given to the Social Indicator and gives same value for other weight coefficients.

### 5.1. Case 1

Case: Resource = Economic = Environment = Social.

This case reflects situation in which all weight coefficients for indicators are the same. This is probably suited while using General Index of Sustainability for the options under consideration. It can be noticed that under this constraint, NGCHP and INCC options are having priority in comparison with other options (Fig. 5).

### 5.2. Case 2

Case: Resource > Economic = Environment = Social.

This case demonstrates the situation when priority is given to the resource indicator. As it can be noticed, IGCC option is the first on the list of the priority among the options under consideration. Also, it is of interest to notice that groups NGT, NGCC and PAFC are having only marginal difference. If this assessment is compared with single parameter analysis, it becomes obvious that there is no difference in the first option rating, but the differences among others are less pronounced (Fig. 6).

### 5.3. Case 3

Case: Economic > Resource = Environment = Social.

The case with priority given to Economic Indicator reflects a strong influence of the other indicators on the priority list for this situation. As expected NGCHP options is the first on the list of priority for this situation. It can be

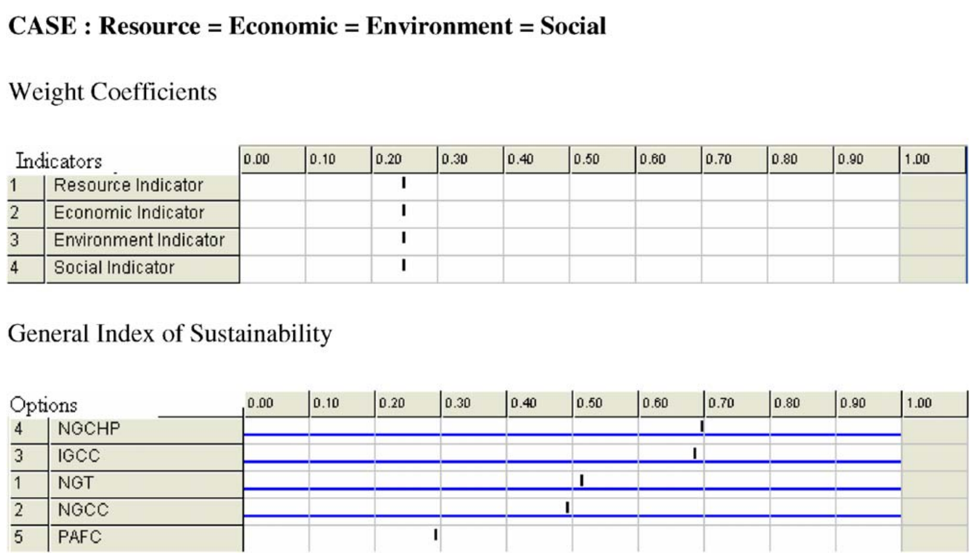


Fig. 5. Case 1. Weight coefficients and general index of sustainability.

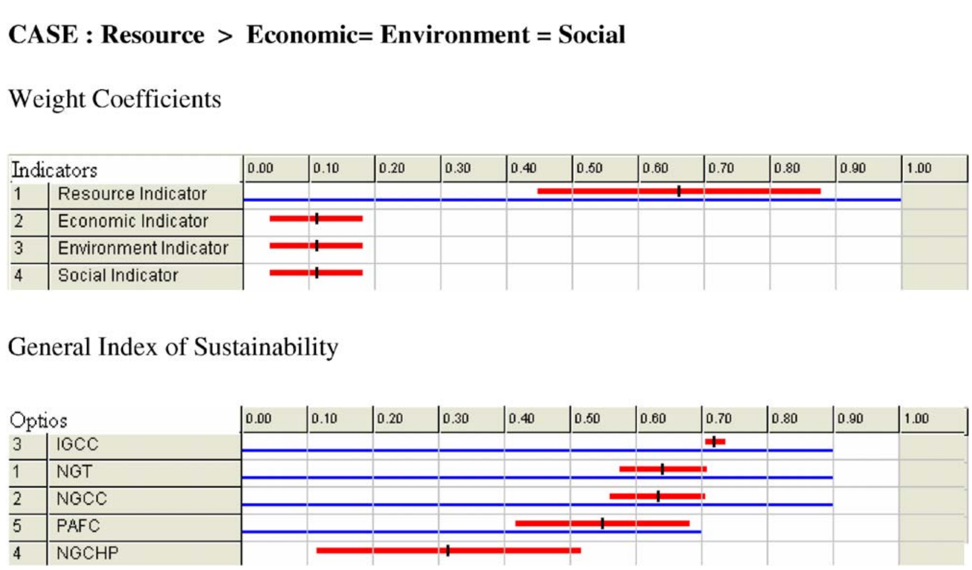


Fig. 6. Case 2. Weight coefficients and general index of sustainability.

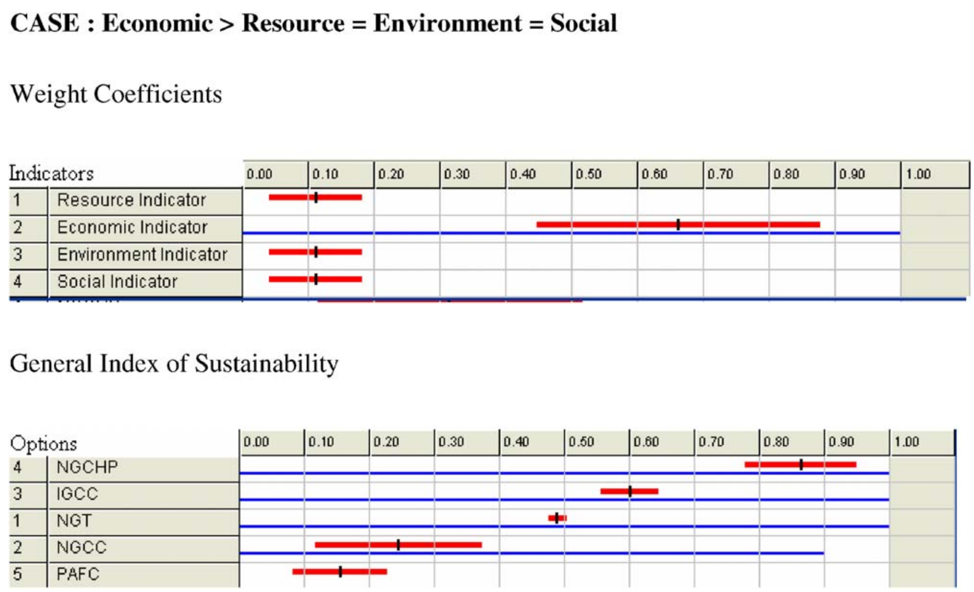


Fig. 7. Case 3. Weight coefficients and general index of sustainability.

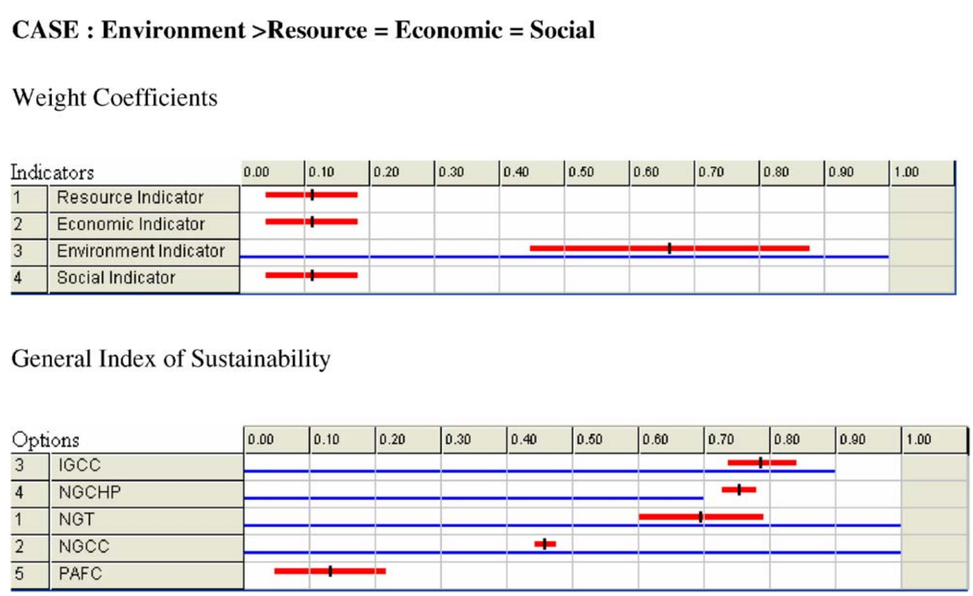


Fig. 8. Case 4. Weight coefficients and general index of sustainability.

noticed that IGCC and NGG substantially lower in comparison with first option. NGCC and PAFC are low rated options in this evaluation. If compared with single parameter analysis there is no difference as regards the first position on priority list, but the difference between other options is substantially pronounced. So, IGGCC and NGCC are very separated in comparison with single-parameter analysis (Fig. 7).

### 5.4. *Case 4*

Case: Environment > Resource = Economic = Social.

With priority given to the Environment Indicator the General Index of Sustainability priority list shows that IGCC, NGCHP and NGT are in the first place. This case has strong differences between groups IGCC, NGCHP and NGT and other options. It is obvious that a small participation of other indicators in comparison with Environment Indicator is rather small and does not aeffect the priority list (Fig. 8).

### 5.5. *Case 5*

Case: Social > Resource = Economic = Environment.

It is becoming important to take into consideration the social aspect of validation in the selection of the energy system. In this case NGCHP has very pronounced value in comparison with IGCC and NGCC while PAFC and NGT

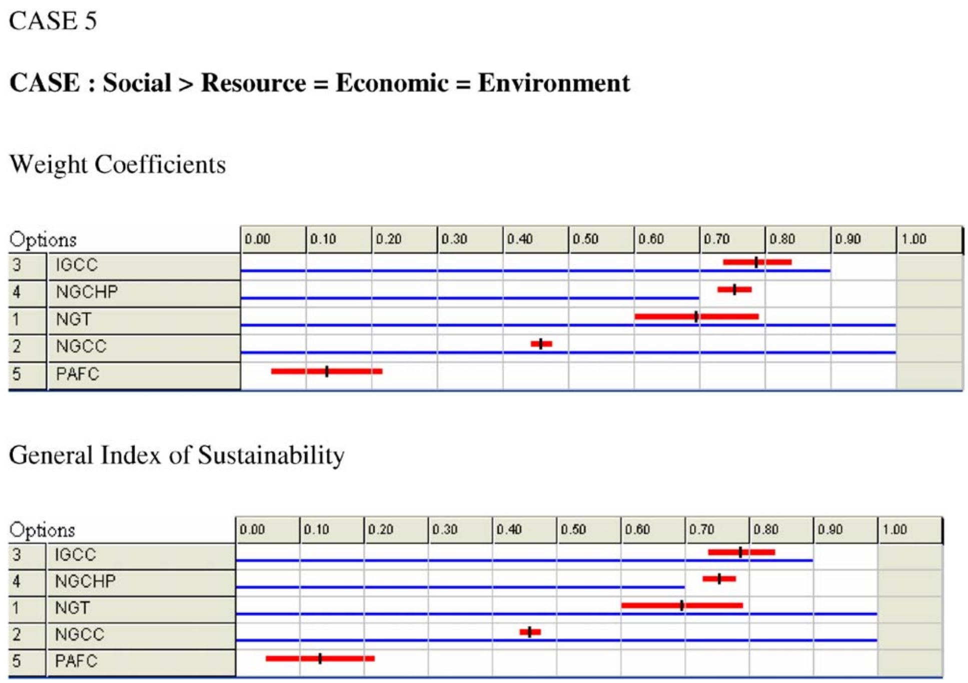


Fig. 9. Case 5. Weight coefficients and general index of sustainability.

have low ratings. It should be emphasized that the case is not very probable (Fig. 9).

## 6. Discussion of muticriteria evaluation

Multi-criteria evaluation of natural gas systems is an exercise showing potential possibility of the analysis of complex systems. In general terms, it could be said that the complexity of natural gas systems can be depicted in a multidimensional space of different indicators. Every energy system under consideration is an entity by itself, defined by the corresponding number of parameters which are deterministically related according to some physical laws describing individual processes in the system. Differences expressed by selected indicators reflect the complexity of individual structure of options under consideration. Sustainability indicators take into the account resources economic, environmental, and social aspect of sustainability. They are supposed to help decision-makers in identifying problematic areas that should be given priority. Specifically, obtained results in sustainability assessment of natural gas systems are indicative as the result of multi-criteria assessment.

As shown in this analysis use of multi-criteria decision-making procedure requires a new method for evaluation of the potential options of energy systems. Its purpose is oriented to the evaluation of options in order to investigate the effect of individual criteria on the priority list for the decision-making process. In this type of evaluation procedure it is possible to investigate effects of mutual relation of the criteria on the final priority list. This evaluation procedure could be imagined as a useful tool for the analysis of individual criteria.

Since each of indicators represents the parameter derived from the internal parameters of the system, the General Index of Sustainability as defined in this analysis is a measure of complexity of the system. Indicators are deterministically related to technical and economic parameters of the system, so their value means only convolution of indicators multiplied by respective weighting coefficients. It is immanent to this type of evaluation that certain arbitrariness creeps in the decision-making procedure. In this respect this procedure of selection of energy system will require further development.

Further development of this methodology will be oriented in two main directions: First, better definition of indicators and their certainty. In particular attention has to be focused on variables affecting indicators which are space and time dependent. Second, use of different types of aggregation functions for the General Index of Sustainability may prove a way of finding respective function appropriate for different systems. As regards the evolution of energy systems, further development of this method may be envisaged through its application to the evaluation future selection of energy systems.

The result obtained in this analysis of natural gas energy systems has shown that in most of the cases NGCHP is the system among the first choice on the priority list independent of the constraints imposed in the decision-making criteria. Also, it is obvious that IGCC system is meeting some of the requirements imposed with specific constraint. Even, high expectation prevailed of the future development of PAFC system, it is obvious that further development is needed before it may be compared with other natural gas energy systems.

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