The Combinatorial Modelling of Vietnam Energy Development

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***Abstract* — The paper describes a combinatorial modelling approach to the research of energy sector development. The idea of the approach is to model a system development in the form of a directed graph with its nodes corresponding to possible states of a system at certain moments of time and arcs characterizing the possibility of transitions from one state to another. The combinatorial modelling is a visual representation of dynamic discrete alternatives. It allows simulating a long-term process of system development under various possible external and internal conditions, and determining an optimal development strategy of the system under study. The formation and analysis procedures of energy development options are implemented in the software package "Corrective". The distributed computing environment is needed to compute an energy sector development graph. In 2015, the Institute of Energy Science of Vietnamese Academy of Science and Technology performed a study on Vietnam sustainable energy development from 2015 to 2030. Based on the data from this study the combinatorial modelling methods are applied to the formation and analysis of Vietnam energy development options taking into account energy security requirements. The constructed Vietnam energy sector development graph consists of 531442 nodes. It is computed on the cluster located at the Institute for System Dynamics and Control Theory of Siberian Branch of the Russian Academy of Science (Irkutsk). The obtained optimal path of Vietnam sustainable energy development provides the minimum costs of energy sector development and operation under deterministic conditions.**

***Index Terms*—combinatorial modelling, energy sector, decision support, distributed computing environment.**

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I. Introduction

The study of long-term energy development with regard to uncertainty (ambiguity) of the initial information and development conditions should be conducted on the basis of general energy research approaches that employ special methods, models, databases and software. The models should consider a rather long time period (30-40 years) and distinguish several stages in the development and operation of energy systems. The models should also explicitly consider discreteness of the energy facility development options. Tools to generate and analyse energy development options must be well-founded and flexible. They should be based on some general organizing research, algorithms to develop and choose energy development options.

There are two approaches to energy models used to project the future energy demand and supply of a country or a region: top-down and bottom-up.

Top-down energy models try to describe the economy as a whole on a national or regional level and to assess the aggregated effects of energy and/or climate change policies in monetary units. These models simulate economic development, related energy demand and energy supply, and employment taking an aggregated view of the energy sector and the economy [1].

A bottom-up energy model has a relatively high degree of technological detail (compared to top-down energy models) used to assess future energy demand and supply. As regards the mathematical form, the bottom-up energy models have been developed in the form of simulation or optimization models, and more recently of multi-agent models [1].

One of the drawbacks of the conventional bottom-up energy model like MARKAL [2], EFOM [3], TIMES [4], MESSAGE [5] opposite to the integrated model of the USA national energy and transportation systems [6] is a complicated way of interregional transport facilities representation at a detailed level.

There are some investigations on the Vietnamese energy sector in literature. The author of [7] employs optimization methods and empirical studies to examine sustainable long-term development in the Vietnamese power sector and determines the ways to implement sustainable energy options for the power sector in practice. In [8] the authors summarize the results of the national Master Plan for developing the electricity supply sector to meet increasing electricity demand. They also describe the evolution and current status of Viet Nam's energy policies, including those related to energy security, energy efficiency and conservation, the environment, and development of renewable energy sources, as well as strategies for power sector development and restructuring of the energy sector toward greater use of competitive energy markets. In [9] the research is focused on the development and implementation of various Energy Efficiency and Conservation policies and programs in Vietnam. The authors of [10] provide an overview of the current energy policies with a view to identify the areas where further policy effort is needed in order to facilitate a sustainable development of the Vietnamese energy sector.

It is impossible to describe and test all distinctive combinations of external conditions and energy development options within the frames of an energy sector model, taking into account uncertainty, energy security threats and other factors. This leads to a huge number of possible energy sector states and takes a lot of time to generate and analyse using usual methods of research. To deal with this issue the combinatorial modelling approach is used. The combinatorial modelling is a visual representation of dynamic discrete alternatives and permits to simulate the long-term process of system development under various possible external and internal conditions, and to determine an optimal development strategy of the system under study.

This paper describes the software that implements some combinatorial modelling approach procedures and considers their application to study some aspects of sustainable energy development of Vietnam under deterministic conditions.

II. Energy Sector Model

The balance mathematical model [11] evaluates the energy sector state at a certain time period with regard to energy security (ES) requirements [12]. The model allows:

- Considering the entire energy sector from production of energy resources to final consumption in various economic sectors including all stages of energy conversion;
- Investigating energy technological and territorial structure development.

The objective function of the energy sector model is

$$(C,X)+\sum(r^t,g^t)\rightarrow min \quad (1)$$

The first component of the objective function reflects the operation costs of the energy sector. The vector C contains specific operating costs for the existing, reconstructed, upgraded and newly built production, transformation and transmission facilities.

The second component represents the losses due to the energy resource shortage for different consumer categories. The energy resource shortage g^t of category t is equal to the difference between R^t and Y^t. Vector r^t consists of the components called "specific losses" for consumer category t.

The objective function of the energy sector model is reduced to the equations:

$$AX - \sum Y^t=0 \quad (2)$$

$$0\leq X\leq D \quad (3)$$

$$0\leq Y^t\leq R^t \quad (4)$$

where $t=1,.., T$ is a category of consumers;
T – the number of consumer categories;
X – the decision vector whose components represent the intensity of energy facilities usage (storage, production, conversion and transmission of energy resources);
Y^t – the decision vector whose components characterize the energy resource consumption for different categories t;
A (the matrix of facility technology factors (production, transformation) and transmission of energy resources;
D – the vector that determines technically possible capacities of production, conversion and transmission facilities;
R^t – the vector that defines energy resources demands of the category t.

III. Combinatorial Modelling Approach

The procedures of the formation and analysis of energy development options are based on the representation of components belonging to an investigated system in the form of a directed graph. The graph nodes correspond to the possible states of the components at certain moments. The graph arcs define the admissibility of transitions between states. The research on the development of the entire system is performed by analysing various combinations of states and transitions of particular components. This approach is known as combinatorial modelling [13].

A component is a structural unit of the system under research. It may be a factory, a power plant, a set of similar energy sources or a consumer category. The degree of aggregation of the energy production or consumption facilities depends mostly on the goals of the study and database capabilities.

The first step of the combinatorial modelling approach is to describe the basic scenario of energy development to investigate as a graph with one node for each time moment

(Fig. 1). These nodes contain essential information to create new possible states of the energy sector.

In the second step, the infrastructure of the energy sector is divided into several components by territorial or industrial criteria. For each component, a development graph is built. It contains changes in the energy facility parameters at the time period considered. The development graphs of two energy facilities are shown in Fig. 2. The source nodes corresponding to moment 0 do not have numbers because they will not participate in the next construction of the energy sector graph.

The third step is combining data of the reference graph with information on different components of graphs belonging to the same moment in time. This results in the set of possible states of the energy sector for each moment in time. The states (nodes) of the modelled system are linked by transitions (arcs) to form an energy sector development graph.

The energy sector development graph shown in Fig. 3 is constructed by means of combination of nodes and arcs of the graphs in Figures 1 and 2. The number of generated possible energy sector state is shown inside the circle in Figure 3. The numbers above the circle are combinations of the graph nodes in Figures 1 and 2. The beginning of all paths in the generated energy sector development graph is a common initial node at moment 0.

The fourth step is to check the validity of nodes and arcs of the energy sector development graph, since not all possible energy sector states and transitions can be valid. For this purpose, there are system-wide constraints in the combinatorial modelling. Two types of them can be distinguished:

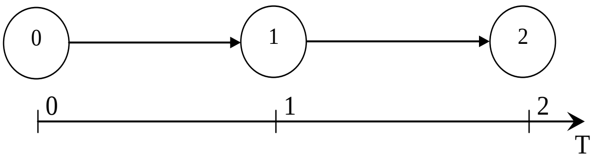

Figure 1. Basic scenario of energy sector development.

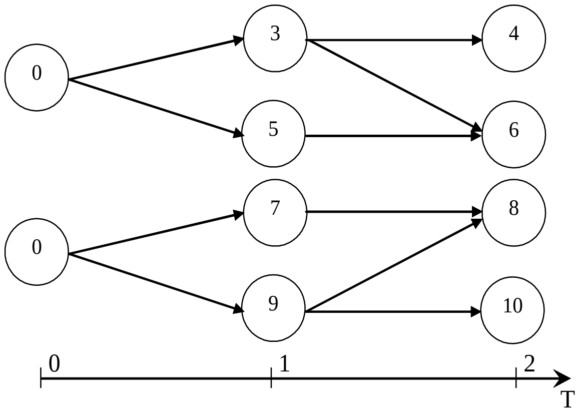

Figure 2. Development graph of two energy facilities.

- Logical conditions. Some development alternatives of a component can depend on the implementation of certain development variants of other components.
- Balance and other design constraints. These are constraints on the available raw resources and products at every time moment and transition. They can be defined by balance equations or inequalities.

Lists of pairs of incompatible nodes are used to implement logical conditions. A couple of incompatible nodes are a pair of nodes of graphs of different components, and their combination with a possible system state is not possible or does not make sense for some reasons.

The model of the energy sector (1) - (4) is of the second type of system-wide constraints. The admissibility of an energy sector state depends on the correctness of the decision results.

If ES requirements exist, then ES status of a possible energy sector state is estimated by means of ES indicators. The ES indicator value is calculated based on the computation results of economic-mathematical model. The ES status is determined by comparing ES indicator values and thresholds.

The energy sector development graph shown in Fig. 3 has four nodes that did not pass the validity check (Fig. 4).

The fifth stage is to build a graph containing valid states and transitions. States and transitions that are unreachable from the initial state are determined during the passage from the initial node to the end nodes. Then, the blind states and transitions are determined during the reverse passage. It is impossible to build a path from the initial node to the nodes with blind states and transitions at the last time moment. The invalid, unreachable and blind states and transitions are removed from the graph which contains possible energy sector states and transitions.

In the last stage, a set of system states to form optimal and suboptimal paths can be determined with the algorithm based on the concept of dynamic programming [14].

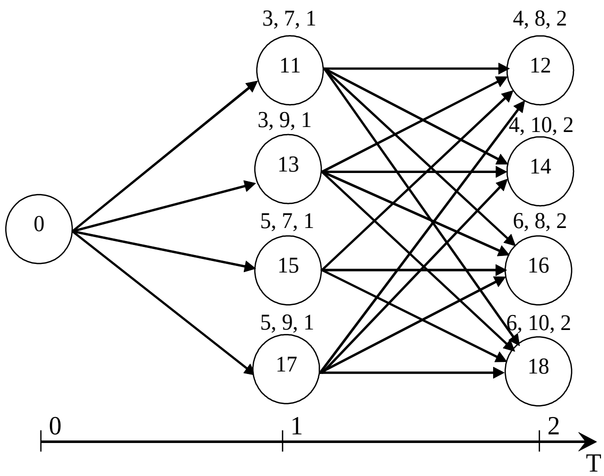

Figure 3. Energy sector development graph.

The graph consisting of valid energy sector states and transitions is shown in Fig. 5. It was made from the graph shown in Fig. 4 where an optimal way to ensure minimization of costs of energy sector development and operation is presented by the bold lines.

The main problem facing the combinatorial modelling methods implementation is a large number of system states and transitions to be simulated. It grows exponentially with the increasing number of system components and their states. That is why the combinatorial modelling approach is usually used with distributed computation technologies [15].

IV. Software Package "Corrective"

The above procedure of the construction and analysis of energy sector development graph is implemented in the software package Corrective [4]. It consists of the following modules:

1. Module m_1 designs a basic scenario of the considered energy sector development,
2. Module m_2 constructs an energy sector development graph,
3. Module m_3 checks the validity of a possible energy sector state (node of development graph),
4. Module m_4 supports expert analysis of energy sector development paths.

Figure 6 depicts a scheme of information and logical links between modules of the Corrective software in the form of a bipartite directed graph where modules m_1, m_2, m_3, m_4 are black ovals.

The main aim of module m_1 is to read information from a database (DB) *A* and to transform it into the basic scenario of energy sector development *B*. DB operates under control of the database management system Firebird.

Module m_2 implements the methods of combinatorial modelling. After constructing the graph, each node is completely independent of others regarding calculations. Total computation time can be significantly reduced with the help of distributed computing technology. This is achieved by dividing the set of *N* nodes into groups of smaller size and processing them simultaneously in a distributed computing environment (DCE). List of input parameters *C* includes specified energy development strategies and can involve ES indicators and disturbances that may occur during the time period considered.

The kernel of module m_2 consists of several tens of scripts written in Lua programming language. The key part of m_2 is the model generator, which generates a new possible state of the energy sector. The generator is controlled by a set of rules that transform raw data *B* and *C* into the components of the energy sector model. Researcher can change these rules.

Module m_3 is used to check the validity of each possible state of the energy sector of set *D* with the multistage constraint system. In the first stage, the energy sector model (1)-(4) is solved as a linear programming problem. If its solution exists, then m_3 can validate ES status by indicative analysis. Finally, the state is added to the set *E*.

Module m_4 enables researchers to identify the optimal energy sector development paths based on set *E*, and to compare the found optimal path with others.

V. Modelling Of Sustainable Development Of Vietnam Energy Sector

The Vietnam energy sector model was developed from 2011 to 2015 on the basis of the energy sector model presented above during the joint research conducted by the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Science (ESI SB RAS) and the Institute of Energy Science of Vietnamese Academy of Science and Technology (IES VAST).

In order to analyse the characteristics of the key socioeconomic regions, the Vietnam energy sector structure and some other related issues, the supply and demand balance is calculated for eight regions: Red River Delta, Northeast, Northwest, North Central, South Central

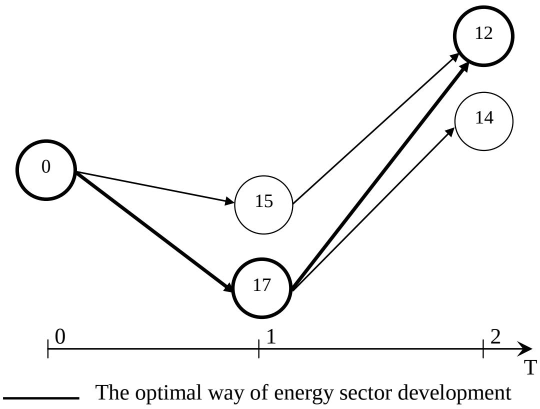

Figure 4. Optimal way on energy sector development graph.

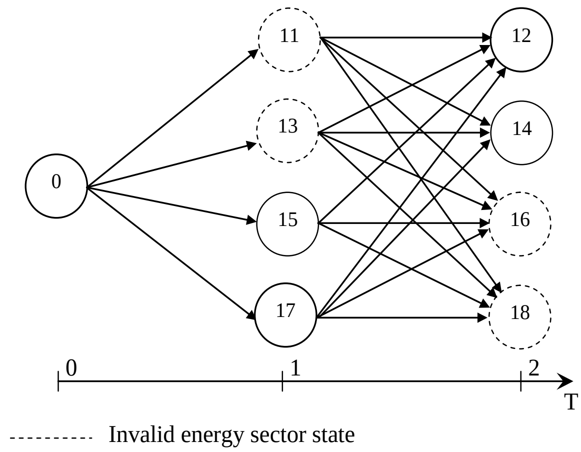

Figure 5. Valid and invalid energy sector states and transitions on energy sector development graph.

Coast, Highlands, Southeast and Mekong Delta. Input data include energy supply (costs and value of production, import and export), conversion and transportation of energy, energy consumption. Specifically, the regional parameters of production capacity, costs of production, transport capacity, transport costs are based on the data from the individual production and transportation facilities. The data on regional energy consumption are obtained and calculated based on energy consumption data for five key economic sectors: industry, agriculture, transportation, commerce- service and residential.

In 2015, IES VAST employed module m_1 to investigate the sustainable energy development of Vietnam from 2015 to 2030, with regard to the energy security requirements. The energy development scenarios are assessed according to energy security and sustainable development criteria. These scenarios should meet the national energy demand for the socioeconomic development; apply the suitable and efficient energy technology, minimize the environmental impacts from the energy system, and achieve the cost-effective energy system development.

Different energy development scenarios for the period of 2020-2030 were built considering capacity variations for the following energy facilities: domestic coal production capacity (baseline, increase by 10 % and decrease by 10 %), domestic natural gas production capacity (baseline, increase by 10 % and decrease by 10 %) and domestic hydropower generation capacity (baseline, increase by 10 % and decrease by 10 %).

Optimally, natural gas capacity should be increased by 2020 to meet the national energy demand, then it should follow the base scenario by 2025 and 2030. Hydropower capacity remains stable for the whole period of 2020-2030, while the coal capacity reduces by 10% by 2020.

Below the algorithms for combinatorial modelling were applied using the same assumptions and data for the formation and analysis of Vietnam energy development.

In the first stage, the basic energy sector development graph was constructed. In the second stage, the component development graphs were built for the pairs of industries and regions of Vietnam (marked with “+” in Table 1). A typical component development graph is shown in Fig. 7, where the component capacity fluctuation is shown in circles.

In the third stage, an energy sector development graph that consists of 531442 nodes is constructed. Each of possible Vietnam’s energy sector states is described by the model (1) - (4) that consists of several thousands of variables and hundreds of equations. In the next stage, the computational experiment on the new energy development graph is performed with DCE, which includes the high-performance cluster Academician V.M. Matrosov [16]. The cluster is located at the Institute for System Dynamics and Control Theory of Siberian Branch of the Russian Academy of Science (Irkutsk).

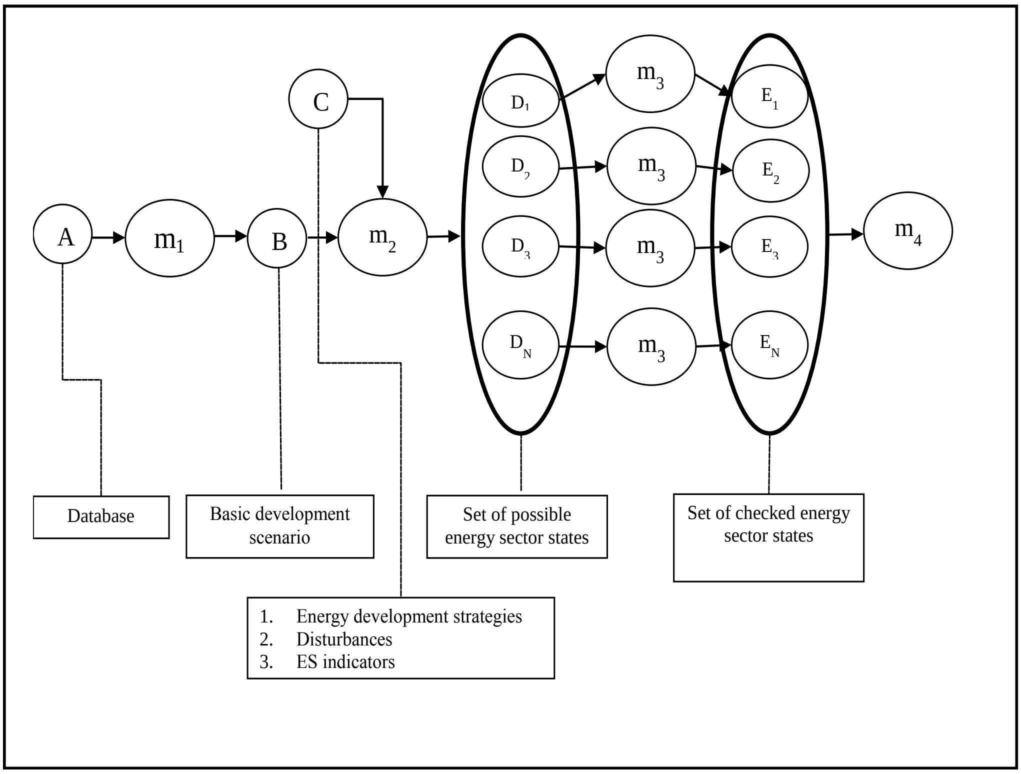

Fig. 6. The logical scheme of software package Corrective.

Table 1. Energy industries and regions of Vietnam.

Region	Domestic coal production	Domestic natural gas production	Domestic hydropower generation
Red River Delta	+		
North East	+		+
North West			+
North Central Coast		+	+
South Central Coast			+
Central Highland			+
South East		+	+
Mekong River Delta		+	

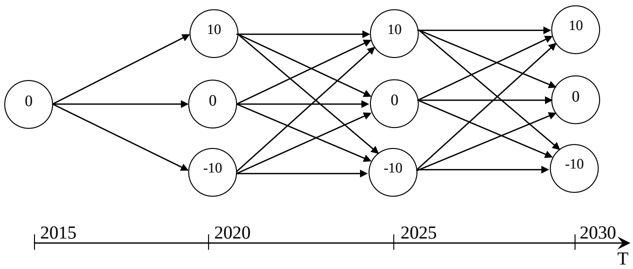

Figure 7. A typical development graph of Vietnam energy industry.

In the fifth stage, we obtain the optimal path with minimum development and operation costs as a criterion, where the natural gas production increases and the coal production reduces for all time moments.

VI. Conclusions

The advantages of the combinatorial modelling are the clarity and compactness of representation of modelled system development options in the form of a directed graph. The graph clearly illustrates both differences of various system development paths and their common states and transitions.

The advantage of this approach is a complete description of the object development options. The traditional approaches to compare the development options based on the multi-criteria methods usually enable researcher to make just a few options. The choice depends on the researcher's intuition and experience. Such selection, even if it is right, always reflects certain subjectivity and thus depreciates the level of result proof.

The resulting set of the admissible system development paths can be applied in many forecasting tasks where, for example, the uncertainty should be taken into account. Among the admissible system paths, one can choose not merely the best way but also the paths close to it according to research criteria.

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