SVRHA I METODE MODELIRANJA ENERGETSKOG SUSTAVA

THE PURPOSES AND METHODS OF ENERGY SYSTEM MODELING

Dr. sc. Helena Božić, Energetski institut Hrvoje Požar,
Savska cesta 163, 10001 Zagreb, Hrvatska
Helena Božić, PhD, Hrvoje Požar Institute for Energy,
Savska cesta 163, 10 001 Zagreb, Croatia

U radu je opisana svrha modeliranja energetskog sustava i podjela modela za planiranje s obzirom na različitosti pristupa i metodologije. Pojava modernih računala i razvoj računalnih programa pojednostavnila je korištenje modela za planiranje. Ovakvi modeli koriste snažne matematičke algoritme i baze podataka koji u relativno kratkom vremenu mogu riješiti vrlo složene probleme. To je dalje omogućilo nastanak tzv. E^3 modela (engl. energy-ecology-economy) koji imaju mogućnost istodobnog sagledavanja pitanja vezanih za energetiku, ali i za ekologiju i ekonomiju. Posebno su prikazane karakteristike modela MARKAL kroz primjer integriranog povezivanja s drugim modelima za planiranje. Pokazuje se da je primjena optimizacijskog modela MARKAL za planiranje energetskog sustava Republike Hrvatske od velikog značenja s obzirom na potrebne analize energetskog tržišta jugoistočne Europe, korištenje obnovljivih izvora energije, energetsku učinkovitost i trgovinu emisijama.

This article describes the purpose of energy system modeling and the classification of planning models according to approaches and methodologies. The advent of modern computers and computer programs has simplified the use of planning models. Such models employ powerful mathematical algorithms and databases which can solve highly complex problems in a relatively short time. This has led to energy-ecology-economy (E^3) models, which are simultaneously able to consider questions in connection with energy supply, ecology and economics. The characteristics of a MARKAL model are presented separately through an example of integration with other planning models. It is demonstrated that the application of an optimizing MARKAL model for the planning of the energy supply system of the Republic of Croatia is of great significance for the analysis of the energy market of South Eastern Europe, the use of renewable energy sources, energy efficiency and emission trading

Ključne riječi: emisije, energetski sustav, linearno programiranje, model MARKAL, planiranje
Key words: emissions, energy system, linear programming, MARKAL model, planning

1 UVOD

Planiranje energetskog sustava složen je proces koji se stalno razvija i nadograđuje. Energetski sustav je kompleksan i sastoji se od više međusobno povezanih subjekata, od strane proizvodnje i dobave energije, preko pretvorbe do strane potrošnje energije. Pojava modernih računala i razvoj računalnih programa pojednostavnila je korištenje modela za planiranje. Takvi modeli koriste snažne matematičke algoritme i baze podataka koji u relativno kratkom vremenu mogu riješiti vrlo složene probleme. To je nadalje omogućilo nastanak tzv. E^3 modela (engl. energy-ecology-economy) koji imaju mogućnost istodobnog sagledavanja pitanja vezanih za energetiku, ali i za ekologiju i ekonomiju. S druge strane, razvitak modela za planiranje omogućava složene analize poput trgovine energijom i emisijama između više povezanih nacionalnih energetskih sustava.

Dosadašnja iskustva u području planiranja energetskog sustava u Republici Hrvatskoj prvenstveno su se odnosila na planiranje energetskih podsustava (elektroenergetskog i plinskog sustava), koji su u procesima planiranja bili međusobno povezani, ali ne i integrirano u jednom modelu. Razvoj energetskog tržišta jugoistočne Europe i potrebe analize područja primjene obnovljivih izvora energije, energetske učinkovitosti i trgovanja emisijama nametnuli su potrebu korištenja integriranih modela, poput modela MARKAL.

2 SVRHA MODELIRANJA ENERGETSKOG SUSTAVA

Zbog složenosti procesa planiranja postavljanje samo jedne definicije koja bi u potpunosti opisala sam proces nije jednostavno, jer se on sastoji od sakupljanja i obrade podataka, izrade scenarija i prognoza potrošnje energije i primjene modela za planiranje. Budući da se svaki model temelji na matematičkim i ekonomskim osnovama, polazna definicija opisuje energetsko planiranje kao procjenu i pronalaženje načina izjednačenja ponude i potražnje za energijom uz sagledavanje ekoloških ograničenja.

Prvi modeli nastali ranih 70-tih godina prošlog stoljeća u vrijeme naftne krize bili su inženjerski modeli. Prilikom postavljanja dugoročnih prognoza potrošnje energije polazilo se od ekonomskih parametara (promjena bruto domaćeg proizvoda, broja stanovnika itd.), gdje je svaka promjena parametara značila i potrebu ponavljanja analize

1 INTRODUCTION

The planning of an energy system is a sophisticated process that is subject to ongoing development and refinement. An energy system is complex and consists of numerous interacting entities, including energy production, supply, transformation and consumption. The advent of modern computers and computer programs has simplified the use of planning models. Such models employ powerful mathematical algorithms and databases which can solve highly complex problems in a relatively short time. This has led to energy-ecology-economy (E^3) models, which are simultaneously able to consider questions in connection with energy supply, ecology and economics. The development of planning models also facilitates complex analyses, such as energy and emission trading among several interrelated national energy systems.

Experience to date in the planning of the energy system in the Republic of Croatia has primarily involved the planning of energy subsystems (the electricity and gas systems), which were mutually linked in the planning processes but not integrated within a single model. The development of the energy market of South Eastern Europe and the need to analyze the areas of the application of renewable energy sources, energy effectiveness and emission trading have made the use of integrated models such as MARKAL models essential.

2 THE PURPOSE OF ENERGY SYSTEM MODELING

Due to the complexity of the planning process, it is difficult to provide an all-encompassing definition to cover the collection and processing of data, the development of scenarios, forecasts of energy consumption and the application of planning models. Since every model is based upon mathematical and economic foundations, a preliminary definition describes energy planning as the assessment and determination of a manner to equalize the supply and demand for energy, taking ecological restrictions into account.

The first models that appeared in the early 1970s during the time of the oil crisis were engineering models. Long-term forecasts of energy consumption started from economic parameters (trends in the gross domestic product, population figures etc.), where each applied parameter required the re-analysis of energy consumption. This was due to the fact that at the time the energy system represented a very small share of the overall economic system. Thus, for example, during the 1970s the energy potrošnje energije. Razlog je bio u činjenici da je tada energetski sustav činio jako maleni dio u ukupnom gospodarskom sustavu. Tako na primjer, 70-tih godina prošlog stoljeća energetski ulaz SAD nije bio veći od 4 % njenog BDP, dok je u Velikoj Britaniji bio oko 5 % [1].

Naftna kriza nametnula je početak razmišljanja o rizicima smanjenja raspoloživosti energetskih izvora kao i rasprave oko primjene nuklearne energije. Time je stvorena podloga za razvitak modela koji su imali mogućnost prikazivanja tehnoloških promjena unutar sustava. Tijekom 70-tih godina prošlog stoljeća uvedena je i mogućnost analize emisije stakleničkih plinova, a usporedno je počela primjena prvih dinamičkih optimizacijskih linearnih modela [2]. Dodatni razvoj i primjena modela nametnuli su potrebu analize utjecaja energetskog sustava na gospodarstvo, što je rezultiralo kombinacijom inženjerskog i ekonomskog modela u jedinstveni model. Primjene modela za planiranje energetskog sustava su raznolike, a kao primjeri mogu se navesti:

- analiza utjecaja između zemalja ili teritorijalnih segmenata unutar jedne zemlje, koji se međusobno razlikuju u klimatskim obilježjima, propisima koji se odnose na emisije stakleničkih plinova, raspoloživosti energetskih izvora, mogućnostima uvoza/izvoza energije i karakteristikama potrošnje,
- analiza novih energetskih tržišta i tehnologija,
- sagledavanje posljedica primjene poreza, subvencija i regulacije na tržištima,
- utjecaj uklanjanja subvencije na određeni energent u energetskom sustavu,
- račun emisija stakleničkih plinova i njihov utjecaj na sustav (mjere za smanjenje emisija, ograničenja na količinu emisija, međunarodne obveze poput Kyoto protokola, trgovanje emisijama),
- izrada studija i planova razvoja i strategije,
- analiza diverzifikacije energenata, sagledavanje ekonomskog i ekološkog utjecaja,
- primjena novih tehnologija za proizvodnju i potrošnju energije,
- povezivanje i međudjelovanje energetskog sustava s gospodarstvom,
- posljedice uvođenja ili prestanka pogona nuklearne elektrane na sustav,
- analiza utjecaja mjera na potrošnju energije na proizvodnju energije i obratno.

Modeli za planiranje koriste se za rješavanje složenih problema zbog čega je najčešće potrebno osigurati velike količine podataka i postaviti više različitih scenarija događaja unutar sustava. Postavljeni model mora biti jednostavan za

input in the United States did not exceed 4 % of the GDP, while in Great Britain it was approximately 5 % [1].

The oil crisis prompted deliberations on the risks of reducing available energy sources as well as discussions on the applications of nuclear energy. Thus, a foundation was created for the development of models that were able to represent technical changes within a system. During the 1970s, it also became possible to analyze emissions of greenhouse gases, and there were early concomitant applications of the first dynamic optimizing linear models [2]. Further development and the application of models made it necessary to analyze the impact of the energy system upon the economy, which resulted in the combining of engineering and economic models into a unified model. The applications of models for the planning of energy systems are varied, and the following examples may be cited:

- analysis of the influences among countries or territorial segments within a country, which differ from each other regarding climatic characteristics, regulations on greenhouse gas emissions, availability of energy sources, options for the import/export of energy and the characteristics of consumption,
- analysis of new energy markets and technologies,
- review of the impact of applied taxes, subsidies and regulations on the market,
- the effect of eliminating subsidies on a particular energy source in the energy system,
- calculation of greenhouse gas emissions and their impact upon the system (measures for reducing emission, restrictions on the quantities of emissions, international obligations such as the Kyoto Protocol and emission trading),
- preparation of studies, development plans and strategies,
- analysis of the diversification of energy sources, survey of the economic and ecological impact,
- application of new technologies for the production and consumption of energy,
- linkage and interaction of the energy system with the economy,
- the consequences of the introduction or the termination of a nuclear power plant on the system,
- analysis of the impact of energy consumption measures on energy production, and energy production measures on energy consumption.

Planning models are used to solve complex problems, for which it is most often necessary to obtain a large quantity of data and present several different scenarios for events within the system. The model presented must be simple to use but at korištenje, ali istodobno mora dovoljno detaljno opisivati promatrane probleme. Pravilo dobro postavljenog modela je njegova razumljivost; kvaliteta dobivenih rezultata ovisit će o iskustvu korisnika modela i kvaliteti ulaznih podataka.

Kriteriji prema kojima se modeli međusobno razlikuju su [3]:

Razina analize – pristupa, vremenskog razdoblja i složenosti problema:

- teritorijalna podjela (globalna, međudržavna, nacionalna, teritorijalna podjela unutar jedne zemlje, lokalna),
- korisnici modela (međunarodne institucije i organizacije, nacionalne institucije, kompanije, pojedinci),
- vremensko razdoblje: jako dugoročno, dugoročno, srednje, kratko, vrlo kratko,
- složenost problema (prema vrstama energije, teritorijalnoj podjeli, funkciji cilja koja se u slučaju linearnih modela može sastojati od jednog ili više parametara),

Analiza dijela energetskog sustava:

- strana potrošnje energije; u modeliranju strane potrošnje energije postoje dva pristupa:

· pristup odozgo prema dolje (engl. top-down approach) – opisuje potrošnju energije na temelju nekoliko osnovnih parametara i koristi statističku analizu za pronalaženje relacije između korištenih indikatora (napr. potrošnja energije je funkcija broja stanovnika, BDP, cijene itd.). Takav pristup prikladniji je za kratkoročne analize, budući da u kratkom vremenskom razdoblju nema većih promjena u parametrima,

· pristup odozdo prema gore (engl. bottom-up approach) – koristi detaljniji pristup, zahtijeva više podataka, uzima u obzir političke odluke i modelira tehničke promjene. Takav pristup bolji je za dugoročne analize. U stvarnosti se koriste kombinacije oba pristupa, na način da se pristup odozgo prema dolje koristi za postavljanje prognoza potrošnje energije, što se dodatno kombinira s modelom za analizu potrošnje energije (pristup odozdo prema gore),

- strana proizvodnje energije,
- kombinirani prikaz strane potrošnje i proizvodnje energije – ravnotežni pristup (engl. equilibrium modelling).

the same time must describe the problems under consideration in sufficient detail. The rule for a well presented model is its understandability. The quality of the obtained results will depend on the expertise of the model user and the quality of the input data.

The criteria for differentiating models may be classified as follows [3]:

Analysis level – approach, time frame and the complexity of the problem:

- territorial division (global, international, national, territorial divisions within a country, local),
- model users (international institutions and organizations, national institutions, companies, individuals),
- time frame: very long term, long term, medium term, short term, very short term,
- problem complexity (according to energy type, territorial division, goal function, which in the case of linear models may consist of one or more parameters),

Analysis of part of the energy system:

- the side of energy consumption; there are two approaches in the modeling of the sides of energy consumption:

· the top-down approach describes the consumption of energy on according to several basic parameters and employs statistical analysis to find correlation among the indicators used. (for example, energy consumption is a function of the number of inhabitants, GDP, prices etc). Such an approach is more suitable for short-term analyses, since there are no major changes in the parameters over a short period of time,

· the bottom-up approach employs a more detailed approach, requires more data, takes political decisions into account and models technical changes. Such an approach is better for long-term analyses. In reality, a combination of both approaches is employed, in such a manner that the top-down approach is used for forecasting energy consumption, which is additionally combined with a model for the analysis of energy consumption (bottom-up approach),

- energy production side,
- a combined presentation of the energy consumption and energy production sides – equilibrium modeling.

Proces modeliranja je složen proces koji obuhvaća [4]:

Postavljanje pretpostavki:

- definiranje ulaznih podataka (baza podataka),
- odabir detaljnosti prikaza problema,

Definiranje modela:

- kalibracija bazne (početne) godine (postavljanje parametara u modelu tako da rezultat proračuna za baznu godinu odgovara stvarnim podacima iz energetske bilance ili vremenske serije podataka),
- definiranje scenarija,
- izrada prognoze potrošnje energije,

Konzultacije s korisnicima rezultata modela:

- pravilno tumačenje rezultata proračuna,
- primjena rezultata u praksi.

Osnova svakog modela za planiranje je integrirani pristup modeliranju, koji se očituje kao međudjelovanje sektora potrošnje (potražnje) i proizvodnje (ponude) energije, kao i povratna veza između cijene i potrošnje energije. Međudjelovanje sektora potrošnje i proizvodnje energije (slika 1) omogućuje sagledavanje utjecaja koje određena promjena u potrošnji energije (npr. primjena mjera upravljanja potrošnjom (DSM) ili uvođenje nove tehnologije) na vrhu mreže, ima na sve podsektore prema njenom dnu. Isto tako vrijedi i princip suprotnog smjera, tj. da promjene u proizvodnji energije (napr. ograničenje energetskih resursa) imaju za posljedicu promjene u potrošnji energije [5].

The modeling process is a complex process that includes the following [4]:

Statement of hypothesis:

- definition of the input data (database),
- selection of the level of detail for presenting the problem,

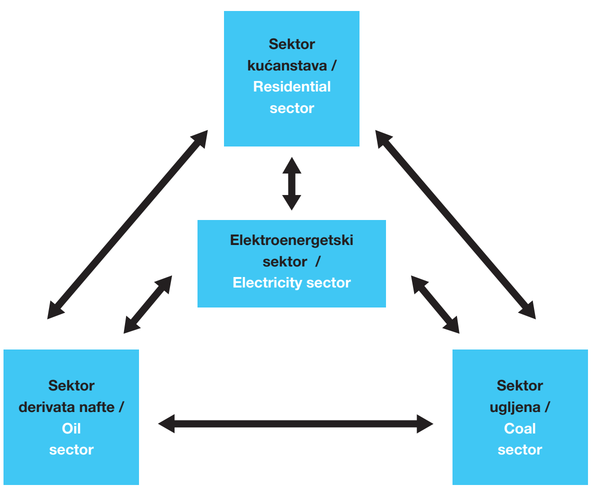
Model definition:

- calibration of the base (initial) year (setting parameters in the model so that the result of the calculation for the base year corresponds to the actual data from the energy balance or the time series of the data),
- definition of the scenarios,
- forecast of energy consumption,

Consultations with the users of the model results:

- correct interpretation of the calculation results,
- applying the results in practice.

The basis of every planning model is an integrated modeling approach to the interaction of the consumption sector (demand) and the production sector (supply), as well as the feedback connection between energy prices and consumption. The interaction of the sectors of energy consumption and production (Figure 1) make it possible to study the effects that certain changes in energy consumption (for example, the impact of the application of demand side management (DSM) measures or the introduction of new technologies) at the top of the network, exerts upon all the subsectors toward the bottom. Likewise, the principle of opposite directions also applies, i.e. changes in energy production (for example, limited energy resources) lead to changes in energy consumption [5].

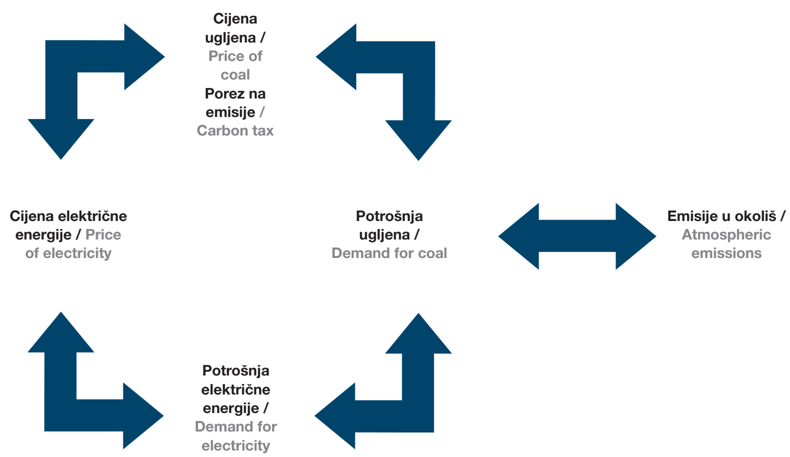


Slika 1
Integrirani pristup modeliranju energetskog sustava
Figure 1
Integrated approach to the modeling of an energy system

Integrirani pristup modeliranju omogućuje i sagledavanje povratne veze između cijene i proizvodnje (potrošnje) energije i samim time emisija u okoliš (slika 2). Svaki model temeljen je na matematičkim postavkama ekonomskih funkcija ponude i potražnje.

An integrated approach to modeling also provides insight into the feedback effect between the prices and production (consumption) of energy and thereby emissions into the environment (Figure 2). Each model is based upon the mathematical precepts of the economic functions of supply and demand.

Slika 2
Integrirani pristup povratne veze između cijene, potrošnje energije i emisija
Figure 2
Evaluation of feedback effects in integrated framework



3 KLASIFIKACIJA MODELA ZA PLANIRANJE ENERGETSKIH SUSTAVA

3.1 Potreba klasifikacije modela

Razvojem informatičke tehnologije došlo je do pojave velikog broja različitih modela za planiranje energetskih sustava. Razlika među modelima je velika s obzirom na njihove mogućnosti i namjene. Iz tog razloga javila se potreba za klasifikacijom modela, da bi se što bolje moglo odrediti koji model je najpogodniji za specifični problem kojeg treba analizirati. U procesu odabira najpogodnijeg modela za prikaz određenog energetskog sustava, potrebno je uzeti u obzir sljedeće:

- prikazivanje energetskog sustava od primarne strane do strane potrošnje ili postavljanje naglaska na određene dijelove sustava (napr. samo strana potrošnje),
- prikazivanje energetskog sustava i promatranje utjecaja na gospodarstvo,
- da li se model želi primijeniti na razvijenu ekonomiju ili zemlju u razvoju ili tranziciji,
- je li potrebno naglasiti projekcije potrošnje, diversifikacije energetskih izvora, međudjelovanje između primarne strane i strane potrošnje, ekološke utjecaje, ili sve zajedno,
- promatra li se nacionalni energetski sustav, ili se radi o teritorijalnoj podjeli unutar sustava,

3 THE CLASSIFICATION OF MODELS FOR THE PLANNING OF ENERGY SYSTEMS

3.1 The need to classify models

With the development of information technology, a large number of various models have appeared for the planning of energy systems. The differences among the models are considerable in terms of their possibilities and purposes. For this reason, the need has arisen for the classification of models, in order to determine which model is the most suitable for a specific problem that must be analyzed. In the process of the selection of the most suitable model for the representation of a specific energy system, it is necessary to take the following into account:

- representation of the energy system from the primary side to the side of consumption or the emphasis of specific parts of the system (for example, only on the consumption side),
- representation of the energy system and analysis of the impact upon the economy,
- whether model is to be applied to a developed economy, a developing country or a country in transition,
- whether it is necessary to place emphasis upon projections of consumption, diversification of energy sources, interaction between the primary side and the consumption side, ecological impact, or all of these together,

– sektore potrošnje obuhvaćene analizom,
– promatrano vremensko razdoblje.

3.2 Podjela modela za planiranje

Postoje karakteristike zajedničke svim energetskim modelima. Tako svaki od njih predstavlja pojednostavnjenu sliku realnosti i uključuje sve aspekte za koje korisnik smatra da su bitni za prikaz sustava. Također svi modeli koji sadrže projekcije buduće potrošnje energije moraju sadržavati i pretpostavke pomoću kojih se definiraju promatrani scenariji. Točnost postavljenih pretpostavki utječe na rezultate dobivene modelskom analizom [6]. Osnovne karakteristike na temelju kojih se modeli međusobno razlikuju su:

– općenite i posebne namjene energetskih modela,
– struktura modela: unutarnje i vanjske pretpostavke,
– analitički pristup: odozgo prema dolje i odozdo prema gore,
– metodologija,
– matematički pristup,
– promatrano područje: globalno, nacionalno i lokalno,
– sektori potrošnje,
– vremensko razdoblje: kratkoročno, srednjoročno i dugoročno,
– zahtjevi za podacima.

3.2.1 Općenite i posebne namjene energetskih modela

Općenite i posebne namjene modela služe za objašnjenje načina prikazivanja budućih zbivanja u modelu s obzirom na:

– Predviđanje buduće potrošnje – Budući da se predviđanje potrošnje energije temelji na ekstrapolaciji trendova potrošnje iz prošlosti, takvi modeli koriste se za analizu relativno kratkoročnih utjecaja. Bitni uvjet koji se postavlja na takve modele je da ključni parametri unutar modela (poput elastičnosti), moraju ostati konstantni tijekom promatranog razdoblja. Takav pristup zahtijeva prikaz ekonomskog ponašanja subjekata unutar modela i uglavnom se primjenjuje u kratkoročnim, ekonometrijskim modelima.
– Istraživanje buduće potrošnje (analiza scenarija) – Istraživanje buduće potrošnje provodi se pomoću analize scenarija, referentnog (osnovnog) i posebnih scenarija. Pretpostavke koje određuju posebne scenarije i što ih razlikuje od referentnog scenarija, odnose se na ograničenje raspoloživosti energetskih izvora, tehnički napredak, gospodarski rast ili

– whether the national energy system or a territorial division within the system is being considered,
– the consumption sectors included in the analysis, and
– the time frame under consideration.

3.2 Classification of planning models

There are characteristics common to all energy models. Thus, each of them represents a simplified picture of reality and includes all the aspects that the user considers to be essential for presenting the system. Furthermore, all models that contain projections of future energy consumption must also contain assumptions according to which the scenarios considered are defined. The accuracy of the assumptions affect the results obtained through model analysis [6]. The basic characteristics according to which models differ from each other are as follows:

– the general and specific purposes of energy models,
– model structure: internal and external assumptions,
– analytical approach: top-down and bottom-up,
– methodology,
– mathematical approach,
– geographical coverage: global, national and local,
– consumption sectors,
– time frame: short term, medium term and long term, and
– data requirements.

3.2.1 The general and specific purposes of energy models

The general and specific purposes of models serve to explain the manner of presenting future events in the model, taking the following into account:

– Consumption forecasting – Since energy consumption forecasts are based on the extrapolation of consumption trends from the past, such models are used for the analysis of relatively short-term impacts. An essential prerequisite assumed for such models is that the key parameters within the models (such as elasticity), must remain constant throughout the observed time frame. Such an approach requires the representation of the economic behavior of the subjects within the model and is generally applied in short-term econometric models.
– Investigation of future consumption (scenario analysis) – Investigation of future consumption is performed with the help of scenario analysis, reference (basic/background) and intervention (specific) scenarios. The assumptions that

rast broja stanovnika. Takav pristup pomoću analize scenarija može se primijeniti kod modela s pristupom odozgo prema dolje i odozdo prema gore.

- Modeli za analizu potrošnje energije – promatraju potrošnju energije kao funkciju promjene broja stanovnika, dohotka i cijena energije.
- Modeli za analizu proizvodnje energije – Temeljeni su uglavnom na tehničkim aspektima energetskog sustava i brinu o zadovoljenju uvjeta ravnoteže između ponude i potražnje energije, ali mogu uključivati i financijske aspekte koji se analiziraju metodom najmanjeg troška.
- Modeli za analizu utjecaja unutar sustava – Utjecaj može uzrokovati postojanje određenog energetskog sustava ili uvođenje posebnih mjera, što može dovesti do promjene financijske situacije, socijalnih odnosa (zapošljavanje) ili utjecaja na zdravlje i okoliš (emisije, otpad).
- Modeli za ocjenu – U slučaju postojanja više opcija one se moraju usporediti i ocijeniti da bi se odabrala najbolja koja odgovara rješenju problema. Kriteriji za usporedbu mogu biti različiti, od kojih se najčešće koristi efikasnost (tehnička i troškovna).

3.2.2 Struktura modela: unutarnje i vanjske pretpostavke

S obzirom na strukturu razlikuju se četiri vrste modela:

- Stupanj endogenizacije – Endogenizacija je pokušaj sagledavanja svih parametara unutar modelskih jednadžbi da bi na taj način broj vanjskih (egzogenih) parametara bio najmanji mogući. Ovakav pristup koriste modeli za predviđanje potrošnje.
- Opis neenergetskih sektora unutar gospodarstva – Komponente neenergetskih sektora uključuju investicije, trgovinu, potrošnju neenergetskih dobara i usluga, raspodjelu dohotka i slično. Pomoću prikaza ponašanja u neenergetskim sektorima, model može analizirati utjecaj mjera energetske politike na gopodarstvo.
- Opis krajnjih sektora potrošnje – uzimajući u obzir detaljniji prikaz sektora krajnje potrošnje energije, model postaje prihvatljiviji za analizu tehnološkog potencijala energetske učinkovitosti.
- Opis tehnologija za proizvodnju energije – Mogućnosti prikazivanja novih tehnologija za proizvodnju energije najbolje se analiziraju modelima koji omogućuju detaljni prikaz tehnologija. Većina modela s ekonomskom pozadinom predstavlja tehnologije vrlo

determine specific scenarios and which differentiate them from reference scenario refer to the limited availability of energy sources, technical progress, economic growth or population growth. Such an approach using scenario analysis can be applied with top-down and bottom-up models.

- Models for the analysis of energy consumption – These models study energy consumption as a function of changes in population figures, income and energy prices.
- Models for the analysis of energy production – These models are generally based upon the technical aspects of the energy system and are concerned with meeting the requirements for equilibrium between energy supply and demand, but can also include the financial aspects that are analyzed using the least-cost method.
- Models for the analysis of endogenous impacts – Impact can be caused by the existence of a particular energy system or the introduction of special measures, which can lead to changes in the financial situation, social relations (employment), or affect health and the environment (emissions, waste).
- Appraisal models – In the event that there are several options, they must be compared and appraised in order to select the best option for solving the problem. The criteria for comparison may be varied, of which the most frequently used is efficiency (technical and cost).

3.2.2 Model structure: internal and external assumptions

Based upon structural differences, there are four types of models:

- Degree of endogenization – Endogenization is the attempt to incorporate all the parameters within model equations in order to minimize the number of external (exogenous) parameters. Such an approach is used in predictive models of consumption.
- Description of the non-energy sectors within the economy – The components of the non-energy sectors include investment, trade, consumption of non-energy goods and services, income distribution etc. By depicting behavior in the non-energy sectors, the model can analyze the impact of energy policy measures on the economy.
- Description of energy end-use sectors – Taking a detailed description of the energy end-use sectors into account, the model is suitable for analyzing the technical potential for energy efficiency.

općenito, poput crne kutije, što ih čini manje pogodnima za analizu različitih tehnologija.

Kod modela kojima vrijednosti parametara nisu određene unutar modela, njihove vrijednosti mora postaviti korisnik. Kao primjeri vanjskih pretpostavki mogu se navesti:

- porast broja stanovnika (uz uvjet da su ostale stvari jednake, porast broja stanovnika uvjetuje porast potrošnje energije),
- gospodarski porast (ima za posljedicu povećanje aktivnosti koje troše energiju i smanjuje vrijeme trajanja energetske opreme),
- potražnja (potrošnja) energije (na potrošnju energije utječu strukturne promjene u gospodarstvu, kao i izbor tehnologija i primjena mjera energetske učinkovitosti),
- ponuda (proizvodnja) energije (određena je raspoloživošću alternativnih izvora energije, proizvodnim tehnologijama i potražnjom energije),
- elastičnost potražnje na cijenu i elastičnost potražnje na dohodak (elastičnost je mjera relativne promjene potražnje za energijom, u odnosu na relativne promjene u cijenama energije i dohocima),
- porezni sustav (utjecaj poreza na ukupne troškove u energetskim sustavima).

3.2.3 Analitički pristup

S obzirom na način povezivanja energetskog sustava i gospodarstva, modeli se mogu podijeliti na dvije osnovne skupine: s ekonomskim pristupom odozgo prema dolje i inženjerskim pristupom odozdo prema gore. Važnost takve podjele modela interesantna je sa stanovišta različitih posljedica njihove primjene, koje nastaju zbog načina korištenja tehnologija, ponašanja gospodarskih subjekata i načina djelovanja tržišta energije. Razlika između pristupa odozgo prema dolje i odozdo prema gore može se definirati kao razlika između općenitog i detaljnog modelskog prikaza, odnosno kao razlika između modela s minimalnim i maksimalnim stupnjem endogenizacije.

Prvi energetski modeli bili su vrlo općeniti modeli s pristupom odozgo prema dolje, gdje je za predviđanje potrošnje korišten samo ekonomski pristup za predviđanje potrošnje energije. Proizvodna funkcija korištena u tim modelima predstavljala je tehnologiju kao crnu kutiju i uključivala je samo općenite varijable za opis energetske potražnje. Kao odgovor na takav pristup, razvili su se prvi oblici inženjerskih simulacijskih modela.

- Description of energy supply technologies –The potential for presenting new technologies for energy production can best be analyzed using models that allow for a detailed description of the technologies. The majority of models with an economic background represent technology in a very general manner, like a black box, which makes them less suitable for analyzing various technologies.

For models in which the parameter values are not assumed within the model, the user will have to make assumptions about the values. Examples of external assumptions include the following:

- population growth (under the condition that other things remain equal, population growth causes increased energy consumption),
- economic growth (results in an increase in activities that consume energy and reduces the working lifetime of energy equipment),
- energy demand (consumption) (affected by structural changes in the economy, as well as the choice of technology and measures of energy efficiency),
- energy supply (production) (determined by the availability of alternative energy sources, production technologies and energy demand),
- price and income elasticities of energy demand (elasticity is a measure of the relative change in energy demand, in comparison to the relative changes in energy prices and incomes),
- tax system (the impact of taxes on the total costs in energy systems).

3.2.3 The analytical approach

Due to the manner in which the energy system and economy are connected, models can be classified into two basic groups: from the economic approach of top-down and the engineering approach of bottom-up. The importance of such model classification is interesting from the standpoint of the differing results of their application, that occur due to the manner in which technology is used, the behavior of economic entities and the manner of the operations of the energy market. The difference between the top-down and bottom-up approaches may be defined as the difference between a general and detailed model representation, i.e. as the difference between models with minimum and maximum degrees of endogenization.

The first energy models were very general models with the top-down approach, where only an economic approach for forecasting energy consumption was used for consumption forecasting. The production function used in these models represented technology as a black box and included

Inženjerski modeli s pristupom odozdo prema gore opisuju tehnike, načine izvođenja i direktne troškove svih tehnoloških opcija u cilju definiranja mogućih poboljšanja i učinkovitosti korištenja tehnologija, uz zanemarenje povratne veze prema gospodarstvu. Takvi modeli obično promatraju samo energetski sustav korištenjem podataka za prikaz sektora potrošnje energije.

U analizi interakcije između energetskog sektora i gospodarstva ekonomski modeli koriste relacije za opis tih sustava. Takvi se modeli mogu koristiti samo uz uvjet da su njihovi parametri određeni na osnovi podataka o potrošnji energije u prošlosti. S druge strane, inženjerski modeli koriste se samo u slučajevima gdje nema povratne veze između energetskog sektora i gospodarstva.

S obzirom na modelsku strukturu, prvi ekonomski modeli imali su visoki stupanj endogenizacije i mogućnosti prikazivanja sektora gospodarstva, dok su prvi inženjerski modeli mogli dobro prikazati krajnje sektore potrošnje i tehnologije za proizvodnju energije. S vremenom su razlike između tih modela postale manje, zahvaljujući mogućnosti kombinacije tih pristupa i razvoja hibridnih energetsko-ekonomskih modela. Takvi su modeli namijenjeni prikazivanju povratne veze između gospodarstva i potrošnje energije, ne uključujući detalje vezano za same tehnologije unutar sektora potrošnje (efekt ekonomske povratne veze).

3.2.4 Podjela modela s obzirom na metodologiju

S obzirom na metodologiju modeli za planiranje mogu se podijeliti na ekonometrijske, makro-ekonomske, modele ekonomske ravnoteže, optimizacijske i simulacijske modele.

Ekonometrijski modeli koriste statističke metode za ekstrapolaciju tržišnih zbivanja i njihovu primjenu u budućnosti i uglavnom se koriste u okviru makroekonomskih analiza. Nedostatak ekonometrijske metode je što ne prikazuje određenu tehnologiju, a zahtjevna je i u pogledu potrebnih podataka.

Glavno obilježje makroekonomskih modela je mogućnost analize gospodarstva i međusobne interakcije među sektorima (poput energetskog sustava kao jednog od sektora) pomoću ulazno-izlaznih tablica. Kao i u slučaju ekonometrijskih modela, primjena makroekonomskih modela zahtijeva relativno visoku razinu iskustva.

Dok se ekonometrijski i makroekonomski modeli uglavnom koriste za analizu kratkoročnih ili srednjoročnih efekata potrošnje energije, modeli

only a general variable to represent energy demand. The first forms of engineering simulation models were developed in response to such an approach.

Engineering models with the bottom-up approach describe the techniques, manners of implementation and direct costs of all the technological options for the purpose of defining potential improvements and the effectiveness of the technologies used, while neglecting the feedback connection with the economy. Such models generally only describe the energy system by using data for the presentation of the energy consumption sector.

In the analysis of the interaction between the energy sector and the economy, economic models use relations for the description of these systems. Such models can only be used under the condition that their parameters are determined on the basis of data on energy consumption in the past. On the other side, engineering models are used only in cases where there is no feedback connection between the energy sector and the economy.

Regarding the model structure, the first economic models had a very high degree of endogenization and the ability to describe the economic sector, while the first engineering models were able to present the end-use sectors of consumption and the technologies for producing energy. With time, the differences between these two models diminished, owing to the possibilities for combining these approaches and the development of hybrid energy-economic models. Such models were intended to show the feedback connections between the economy and energy consumption, without including details connected with the technologies within the consumption sector (the effect of economic feedback connection).

3.2.4 Classification of models according to methodology

Regarding methodology, planning models can be classified as econometric, macroeconomic, economic equilibrium, optimization and simulation models.

Econometric models use statistical methods for the extrapolation of market events and their application in the future. They are generally applied within the framework of macroeconomic analyses. A shortcoming of the econometric method is that it does not represent specific technologies, and it is demanding in respect to the data required.

The chief characteristic of macroeconomic models is the possibility for the analysis of the economic and mutual interactions among sectors (such as the energy system as one of the sectors) using ekonomske ravnoteže koriste se za dugoročne analize energetskog sektora i njegove povezanosti s gospodarstvom. Modeli ekonomske ravnoteže dijele se na modele djelomične i potpune ravnoteže ili modele optimalnog porasta. Modeli djelomične ravnoteže usmjereni su na prikazivanje ravnoteže u pojedinim dijelovima gospodarstva, kao što je ravnoteža između potrošnje i proizvodnje energije. Modeli potpune ravnoteže promatraju ravnoteže na svim tržištima promatranog gospodarstva, s naglaskom na prikazivanje povratnih veza među pojedinim tržištima.

Optimizacijski modeli koriste metodologiju optimizacije za postizanje optimalnih investicijskih strategija. Osnovni uvjet postizanja optimalnog rješenja problema jest zadovoljenje zadanih ograničenja u energetskom sustavu (poput ograničenja raspoloživosti primarne energije i emisije stakleničkih plinova).

Simulacijski modeli su opisni modeli temeljeni na logičkom prikazu sustava i dijele se na statičke (promatraju samo jedno razdoblje) i dinamičke (na rezultat jednog razdoblja utječu rezultati iz prijašnjih razdoblja) i koriste se za analize scenarija potrošnje energije.

3.2.5 Matematički pristup u modelima za planiranje

Najčešće korištene matematičke tehnike u energetskim modelima su linearno, mješovito-cjelobrojno i dinamičko programiranje.

Linearno programiranje je matematička tehnika temeljena na principu maksimiziranja ili minimiziranja zadanog kriterija uz zadana ograničenja. Mješovito-cjelobrojno programiranje razvilo se kao nastavak linearnog programiranja i primjenjuje se za analize čiji su rezultati cjelobrojni. Dinamičko programiranje je metoda koja polazni problem dijeli na više manjih problema i za svaki od njih pronalazi optimalno rješenje.

U novije vrijeme koriste se modeli s tehnikom stohastičkog i Fuzzy-linearnog programiranja za rješavanje problema postojanja neodređenosti u vrijednostima parametara, podataka i varijabli odlučivanja (rješenja linearnog programa) [7].

3.2.6 Promatrano područje: globalni, nacionalni i lokalni modeli za planiranje

Globalni modeli opisuju stanje u svjetskoj energetici, nacionalni modeli prikazuju model energetskog sustava određene zemlje, a lokalnim

input-output tables. As in the case of econometric models, the application of macroeconomic models requires a relatively high level of experience.

While econometric and macroeconomic models are chiefly used for the analysis of the short-term or medium-term effects of energy consumption, economic equilibrium models are used for the long-term analysis of the energy sector and its linkage with the economy. Economic equilibrium models are divided into partial equilibrium models and general equilibrium models or optimal growth models. Partial equilibrium models are focused on presenting equilibria in individual parts of the economy, such as the equilibrium between energy consumption and production. General equilibrium models consider the equilibria in all the markets of the economy being studied, with emphasis on presenting the feedback connections among individual markets.

Optimization models use optimization methods in order to reach optimal investment strategies. The basic requirement for achieving an optimal solution to a problem is meeting the given constraints in the energy system (such as constraints on the availability of primary energy and greenhouse gas emissions).

Simulation models are descriptive models based upon the logical representation of a system and can be static (considering only one time period) or dynamic (the result of a time frame are affected by the results of previous periods) and are used for the analysis of energy consumption scenarios.

3.2.5 The mathematical approach in planning models

The most commonly used mathematical techniques in energy models are linear, mixed-integer and dynamic programming.

Linear programming is a mathematical technique based upon the principle of maximizing or minimizing a defined criterion, subject to the operative constraints. Mixed-integer programming developed as a continuation of linear programming and is applied to analyses in which the results are integers. Dynamic programming is a method that divides the original problem into several sub-problems and finds the optimal solution for each of them.

Recently, models with stochastic and fuzzy-linear programming have been used for solving problems with some uncertainty in the parameters, data and variables of decision making (linear program solutions) [7].

se modelima analiziraju manje teritorijalne cjeline unutar jedne zemlje, poput županije ili grada.

3.2.7 Promatrani sektori potrošnje energije

Modeli mogu biti namijenjeni analizi samo jednog sektora potrošnje energije, kao što je slučaj za većinu inženjerskih modela, ali postoje i modeli za analizu više sektora istodobno. Kod ovakve podjele modela ključna pretpostavka je način podjele gospodarstva na određene sektore. Modeli koji promatraju više sektora gospodarstva mogu se koristiti za analize na globalnoj, nacionalnoj i lokalnoj razini, uz postojanje međusobne interakcije svih sektora. Modeli sa samo jednim sektorom (energetski sustav) promatraju isključivo taj sektor ne uzimajući u obzir makroekonomske veze tog sektora i ostalih sektora.

3.2.8 Vremensko razdoblje: kratkoročno, srednjoročno i dugoročno

Budući da ne postoji standardna definicija koja određuje duljinu kratkoročnog, srednjoročnog i dugoročnog razdoblja, može se okvirno definirati trajanje kratkoročnog razdoblja u iznosu od 5 ili manje godina, srednjoročnog između 5 i 15 godina i dugoročnog 15 ili više godina.

3.2.9 Zahtjev za podacima

S obzirom na vrstu podataka potrebnih za analizu promatranog sustava, postoji razlika između vrsta podataka (novčani, energetski) i manje ili više detaljnih podataka.

3.3 Primjeri modela za planiranje energetskih sustava

Najčešće korišteni modeli za planiranje energetskih sustava su optimizacijski modeli. Njihova dodatna podjela moguća je s obzirom na kriterije:

- broj vremenskih razdoblja – statički (jedno vremensko razdoblje) ili dinamički (više razdoblja),
- modelski parametri – mogu biti konstantne veličine (deterministički model), definirani kao slučajne veličine (stohastički model) ili se mogu mijenjati sistematički (parametrijski model),
- ponašanje varijabli u optimalnom rješenju – varijable mogu poprimiti bilo koju vrijednost koja zadovoljava ograničenja (kontinuirani model), diskretne vrijednosti (cjelobrojni ili diskretni model), odnosno kontinuirane i cjelobrojne vrijednosti (engl. mixed model).

3.2.6 Geographical coverage: global, national and local planning models

Global models represent the world energy situation, national models represent a model of the energy system of a specific country, and local models analyze smaller territorial entities within a country, such as a county or city.

3.2.7 Coverage of energy consumption sectors

Models can be intended for the analysis of only a single sector of energy consumption, as is the case for the majority of engineering models, but there are also models for the analysis of several sectors at the same time. A key assumption in such modeling is the manner of dividing the economy into certain sectors. Models that cover several sectors of the economy can be used for analysis on the global, national and local levels, with mutual interaction among all the sectors. Models with only one sector (energy system) focus exclusively on that sector, without taking into account the macroeconomic linkages between that sector and other sectors.

3.2.8 Time period: short-term, medium-term and long-term

Since there is no standard definition that determines the length of short-term, medium-term and long-term time frames, it is generally possible to define a short-term time frame as 5 years or less, between 5 and 15 years for medium-term time frame and 15 years or more for a long-term time frame.

3.2.9 Data requirements

Regarding the type of data required for the analysis of a system, there are differences among the types of data (monetary, energy) as well as more or less detailed data.

3.3 Examples of energy planning system models

The most commonly used models for the planning of energy systems are optimization models. It is possible to classify them further, according to the following criteria:

- the number of time periods – static (one time period) or dynamic (several periods),
- model parameters – can be of constant values (deterministic model), defined as chance values (stochastic model) or it can change systematically (parametrric model),
- behavior of variables in the optimal solution – variables can assume any value that meets the constraints (continuous model), discrete values (integer or discrete model), or continuous and integer values (mixed model).

Dinamički optimizacijski modeli kao inženjerski modeli koriste mogućnost savršenog predviđanja, tj. donošenja ekonomski optimalnih rješenja na temelju potpunog poznavanja budućih parametara u sustavu. Primjer modela koji prikazuju isključivo energetski sustav su optimizacijski modeli poput MARKAL (MARKet ALlocation), MESSAGE (Model for Energy Supply System Alternatives and their General Environmental Impacts), EFOM (Energy Flow Optimisation Model) i TIMES (The Integrated Markal Efom System) [4].

Uza sve prednosti dinamičkih optimizacijskih modela nedostatak im je što ne prikazuju ponašanje potrošača i zanemaruju vezu potrošnje i cijene energije (što nije slučaj za model MARKAL gdje postoji nadogradnja modela s obzirom na mogućnost korištenja parametara elastičnosti).

Modeli s kombiniranim inženjerskim i ekonomskim pristupom poput modela MARKAL-MACRO mogu optimizirati povezanost gospodarstva i energetskog sustava. Dok model MARKAL koristi inženjerski pristup odozdo prema gore i na taj način prikazuje energetski sustav s bogatom bazom podataka, prikaz gospodarstva modelom MACRO prilično je jednostavan.

Model MACRO definira dugoročni gospodarski razvitak kao agregatnu ponudu prikazanu pomoću funkcije proizvodnje. Promatrana funkcija spada u grupu CES razgranatih proizvodnih funkcija (engl. constant elasticity of substitution), koje se sastoje od klasičnih proizvodnih faktora (kapitala i rada) s pridruženim faktorom energije (budući da je obuhvaćen i energetski sustav kao dio gospodarstva), s mogućom supstitucijom među faktorima proizvodnje. Upravo ovakva proizvodna funkcija predstavlja vezu između inženjerskog (MARKAL) i ekonomskog modela (MACRO) [8].

4 OPIS MODELA MARKAL

Model MARKAL je dinamički optimizacijski model koji koristi matematičku tehniku linearnog programiranja za prikazivanje kompleksnih energetskih sustava na globalnoj, nacionalnoj ili lokalnoj razini planiranja. Model optimizira promatrani energetski sustav uz uvjet najnižeg troška, gdje objektna funkcija predstavlja sumu diskontiranih ukupnih troškova sustava (od strane proizvodnje do strane potrošnje energije). Minimizacija ukupnih troškova sustava temelji se na pretpostavkama da je proizvodnja energije veća ili jednaka potrošnji energije, potrošnja energije je u potpunosti zadovoljena kao i ograničenje na raspoloživost primarnih oblika energije [9].

Dynamic optimizing models such as engineering models use the assumption of perfect foresight, i.e., yielding economically optimal solutions on the basis of the complete knowledge of the future parameters in the system. Examples of models that present energy systems exclusively are optimizing models such as MARKAL (MARKet ALlocation), MESSAGE (Model for Energy Supply System Alternatives and their General Environmental Impacts), EFOM (Energy Flow Optimization Model) and TIMES (The Integrated Markal Efom System) [4].

Besides all the advantages of dynamic optimizing models, one of their shortcomings is that they do not represent consumer behavior and neglect the linkage between consumption and energy prices (which is not the case for the MARKAL model, where there is an addition to the model regarding the option to employ elasticity parameters).

Models with a combined engineering and economic approach such as the MARKAL-MACRO are able to optimize the linkage between the economy and energy system. While MARKAL uses a bottom-up engineering approach and thereby represents an energy system with a rich database, the representation of the economy with the MACRO model is fairly simple.

The MACRO model defines long-term economic development as the aggregate supply represented using the production function. This function belongs to the group of the constant elasticity of substitution (CES) production functions, which consists of the classical production factors (capital and labor) with the associated energy factor (since the energy system is also included as a part of the economy), with the option of substitution among the production factors. Such a production function represents the linkage between the engineering model (MARKAL) and economic model (MACRO) [8].

4 DESCRIPTION OF THE MARKAL MODEL

The MARKAL model is a dynamic optimizing model that uses mathematical linear programming technique for the representation of complex energy systems on the global, national or local planning level. The model optimizes the studied energy system with the constraint of least-cost, where the objective function represents the sum of the total discounted system expenditures (from energy production to consumption). Minimization of the total system expenditures is based upon the assumptions that energy production is greater than or equal to energy consumption, energy

4.1 Model nacionalnog energetskog sustava

U planiranju nacionalnog energetskog sustava Republike Hrvatske koriste se modeli poput ENPEP i MESSAGE te model MARKAL, koji ima niz prednosti u odnosu na prva dva spomenuta. Osim jednostavnosti korištenja (u odnosu na model MESSAGE) i tehnike optimizacije (u odnosu na model ENPEP), MARKAL model omogućuje integrirani prikaz proizvodnje i potrošnje energije uz mogućnosti postavljanja dodatnih ograničenja (napr. emisije stakleničkih plinova), a ima i veći broj korisnika.

MARKAL model nacionalnog energetskog sustava Republike Hrvatske, prikazan na slici 3, sastoji se od više povezanih dijelova, od strane proizvodnje energije, pretvorbe energije u postrojenjima za energetske transformacije i elektroenergetskom sektoru, do strane potrošnje energije u različitim sektorima potrošnje. Proizvodnja energije definirana je podacima o proizvodnji i uvozu primarnih oblika energije u baznoj godini s pripadajućim troškovima. Osim podataka za baznu godinu, potrebno je postaviti prognozu promjene troškova proizvodnje, uvoza i raspoloživosti primarnih izvora energije.

Sustav plinovoda prikazan je odvojeno kao transportni i distrubucijski sustav, svaki sa svojim karakteristikama i potrošačima, s obzirom da direktni potrošači (direktno priključeni na transportnu mrežu plinovoda) čine 67 % ukupne potrošnje prirodnog plina. Ulazni podaci potrebni za model plinskog sustava su iznos gubitaka, kapacitet i životni vijek plinovoda, specifične investicije za izgradnju novih plinovoda i troškovi održavanja. Na sličan način definira se i sustav transporta sirove nafte.

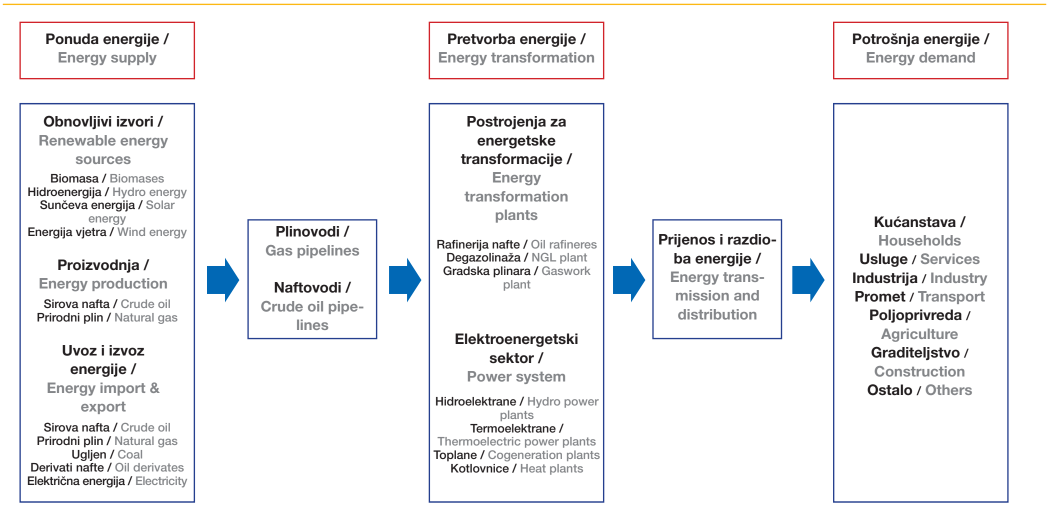
consumption requirements are met completely, as are the constraints on the availability of primary forms of energy [9].

4.1 Model of the national energy system

In the planning of the national energy system of the Republic of Croatia are used models such as ENPEP and MESSAGE and also model MARKAL, which have multiple advantages in comparison to those first two mentioned. In addition to simplicity of use (in comparison to the MESSAGE model), and optimizing technique (in comparison to the ENPEP model), the MARKAL model facilitates an integrated representation of energy production and consumption with the option of the posing of additional constraints (for example, on greenhouse gas emissions), and has a larger number of users.

The MARKAL model of the national energy system of the Republic of Croatia, presented in Figure 3, consists of several linked parts, from energy production, transformation in plants for energy transformation and the electricity sector, to energy consumption in various consumption sectors. Energy production is defined by data on the production and import of primary energy forms in the base year with the corresponding expenditures. In addition to data for the base year, it is necessary to forecast changes in the expenditures of production, import and the availability of primary energy sources.

The system of gas pipelines is represented separately as a transport and distribution system, each with its own characteristics and consumers, regarding direct consumers (directly connected to the gas pipeline network) comprising 67 % of the total natural gas consumption. The input data required for the gas system model are the amount of loss, capacity and lifetime of pipelines, specific investments for the construction of new gas pipelines and maintenance costs. The system for the transport of crude oil is defined in a similar manner.



Slika 3
Struktura MARKAL modela nacionalnog energetskog sustava Republike Hrvatske
Figure 3
MARKAL model structure of the national energy system of the Republic of Croatia

Proizvodnja transformiranih oblika energije (električna energija, para i topla voda, tekuća goriva) odvija se u postrojenjima za energetske transformacije (rafinerije nafte, degazolinaža, gradska plinara) i u postrojenjima elektroenergetskog sektora (hidroelektrane, termoelektrane, javne i industrijske toplane i kotlovnice). Kogeneracijska postrojenja (javna i industrijska) za proizvodnju električne i toplinske energije prikazana su kao protutlačni procesi (odnos između proizvedene električne energije i topline je konstantan). Za sva postrojenja koja koriste loživo ulje, model omogućava supstituciju loživog ulja prirodnim plinom u skladu s uvjetom najmanjeg troška.

Gubici prijenosa i distribucije električne i toplinske energije u modelu MARKAL prikazani su indirektno pomoću posebnih parametara koji uključuju specifične investicije u izgradnju mreže, troškove pogona i održavanja i postotni iznos gubitaka.

Strana potrošnje energije u mreži energetskog sustava Republike Hrvatske sastoji se od tehnologija za potrošnju energije i zadane potrošnje korisne energije (engl. demand). Potrošnja energije može se prikazati kao finalna (poput potrošnje električne energije za netoplinske namjene u kućanstvima) i korisna energija (poput potrošnje energije za grijanje). Detaljnost prikaza strane potrošnje energije u energetskom sustavu ovisi o raspoloživim podacima i vrsti modela.

The production of transformed forms of energy (electricity, steam and hot water, liquid fuels), takes place in energy transformation plants (oil refineries, NGL plants, gasworks) and in plants in the electrical sector (hydroelectric power plants, thermoelectric power plants, public and industrial cogeneration plants and heat plants). Cogeneration plants (public and industrial) for the production of electricity and thermal energy are represented as back pressure processes (the ratio between the electricity and heat produced is constant). For all the plants currently applying heating oil, the model permits the eventual substitution of natural gas for heating oil, according to the least-cost requirement.

Losses during the transmission and distribution of electricity and heat energy in the MARKAL model are represented indirectly using separate parameters that include specific investments in network construction, plant expenditures and maintenance, and the percentage amount of loss.

The energy consumption side in the energy system network of the Republic of Croatia consists of technology for energy consumption and the given consumption of useful energy (demand). Energy consumption can be represented as final (such as the complete consumption of electricity for non-heating purposes in households) and useful energy (such as the complete consumption of energy for heating). The degree of detail in the representation of the sides of energy consumption in the energy system depends upon the available data and the type of model.

4.2 Model teritorijalno segmentiranog energetskog sustava

Osim nacionalnog energetskog sustava model MARKAL može analizirati i više međusobno povezanih sustava, bilo da se radi o zasebnim nacionalnim sustavima ili teritorijalnim segmentima unutar jednog nacionalnog sustava. U slučaju analize više povezanih nacionalnih sustava promatra se model energetskog tržišta (napr. tržište energije jugoistočne Europe). Pojedinačni sustavi međusobno su povezani vezama (linkovima) za bilateralnu trgovinu energijom i emisijama, koja se odvija zbog razlike u troškovima proizvodnje i pretvorbe energije između sustava iz kojeg se ona izvozi i sustava u koji se energija uvozi.

Potreba analize potrošnje energije teritorijalno segmentiranih energetskih sustava nastala je zbog razlike u geopolitičkim i zemljopisnim obilježjima, strukturi gospodarstva i energetskoj opskrbi, mogućnosti proizvodnje primarnih oblika energije (prvenstveno prirodnog plina i sirove nafte) i električne energije, kao i razlikama u emisijama stakleničkih plinova. S obzirom na strukturu sustava i potrebne podatke, način prikazivanja modelom MARKAL svakog od segmenata unutar nacionalnog sustava jednak je prikazu jednog (nacionalnog) sustava, tj. elemente nacionalnog energetskog sustava potrebno je raspodijeliti s obzirom na promatrane segmente.

Primjer analize teritorijalno segmentiranih energetskih sustava kao dijelova energetskog sustava Republike Hrvatske zanimljiv je za slučaj izgradnje plinovoda u području koji nije plinoficirano (Dalmacija) a time i izgradnje elektroenergetskih objekata (termoelektrana i kogeneracijskih postrojenja) na plin. Ovakav model ujedno rješava pitanje buduće opskrbe prirodnim plinom (dodatni uvoz iz Mađarske ili gradnja LNG terminala u priobalnom pojasu). U slučaju međusobno povezanih nacionalnih sustava susjednih zemalja, ovakva analiza može odgovoriti na pitanje o opravdanosti izgradnje međunarodnih sustava transporta prirodnog plina i nafte.

4.2 Model of a territorially segmented energy system

In addition to the national energy system model, MARKAL can also analyze several mutually linked systems, whether this concerns a discrete national systems or a territorial segments within a national system. In the case of an analysis of several linked national systems, a model of the energy market is studied (for example, the energy market of South Eastern Europe). Individual systems are mutually linked for bilateral energy and emission trade, which occurs due to the differences in the expenditures for energy production and transformation between the system from which energy is exported and the system in which energy is imported.

The need to analyze the energy consumption of territorially segmented energy systems occurred due to the differences in the geopolitical and geographical characteristics, structures of the economies and energy supply, the possibilities for the production of primary forms of energy (with natural gas and crude oil in the first place) and electricity, as well as the differences in the emissions of greenhouse gases. Considering the structure of the systems and the necessary data, the manner of representing each of the segments within a national system using the MARKAL model is the same as the representation of a single (national) system, i.e. the elements of a national energy system must be divided according to the segments studied.

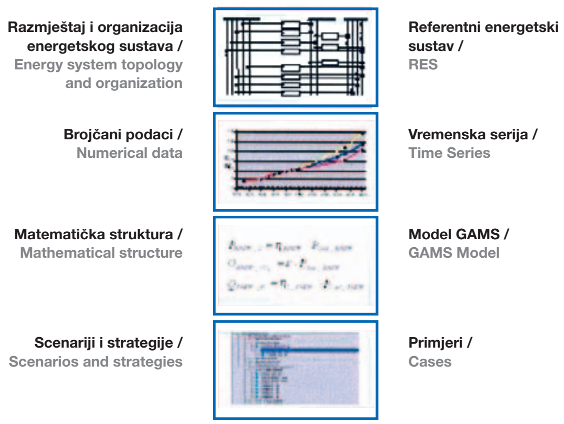
The example of the analysis of territorially segmented energy systems as parts of the energy system of the Republic of Croatia would be interesting in the case of the construction of a gas pipeline in a region which is not gassified (Dalmatia), and therefore also the construction of thermoelectric and cogeneration plants using gas. Such a model at the same time solves the question of the future natural gas supply (additional import from Hungary or the construction of LNG terminals in the coastal belt). In the case of the mutually linked national systems of neighboring countries, such an analysis can answer the question of the justification of the construction of international transport systems for natural gas and oil.

5 PRETPOSTAVKE ZA PRIMJENU MODELA MARKAL

Planiranje energetskog sustava modelom MARKAL zahtijeva detaljni prikaz svih načina proizvodnje, pretvorbe, prijenosa, distribucije i sektora potrošnje energije, što istodobno zahtijeva poznavanje i unos velikog broja različitih podataka. Svaki linearni model je programski paket sastavljen od više međusobno povezanih komponenata (slika 4). Početak rada s takvim modelom pretpostavlja definiranje strukture referentnog energetskog sustava (engl. Reference Energy System, RES) i baze ulaznih podataka (unosom podataka putem korisničkog sučelja) od strane korisnika modela. Slijedi postavljanje matematičke strukture, tj. matrice linearnih jednadžbi pomoću generatora matrice (korištenjem programskog jezika GAMS). Određivanjem scenarija događaja u potpunosti je završen proces postavljanja problema. Pokretanjem matematičkih algoritama dobiva se optimalno rješenje za postavljeni scenarij [10].

5 ASSUMPTIONS FOR THE APPLICATION OF THE MARKAL MODEL

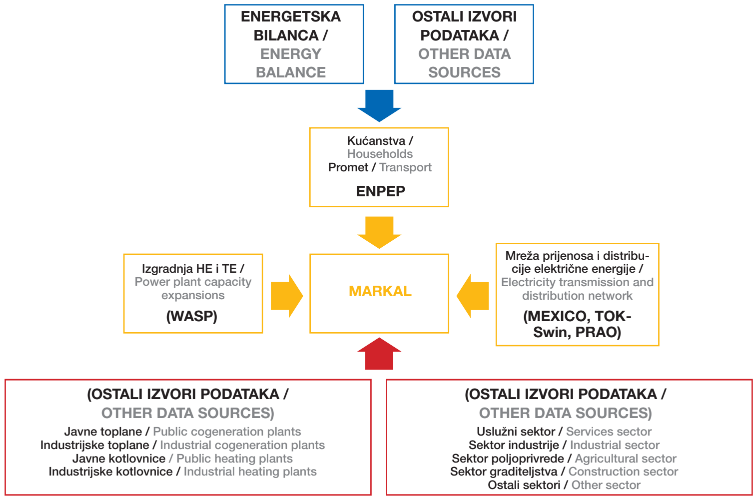
Energy system planning with the MARKAL model requires a detailed representation of all the types of production, transformation, transport, distribution and the energy consumption sectors, which at the same time requires knowledge and entry of a large number of various data. Each linear model is a program package consisting of several mutually linked components (Figure 4). The beginning of work with such a model involves the definition of the structure of the reference energy system (RES) and the input database (data entry via the user's interface) from the side of the model user. This is followed by the setting up of the mathematical structure, i.e. a matrix of linear equations using the matrix generator (in the GAMS programming language). With the determination of the scenario of events, the process of posing the problem is fully completed. Through the use of mathematical algorithms, the optimal solution for the scenario is obtained [10].



Slika 4 Komponente modela energetskog sustava
Figure 4 Components of an energy system model

Izvori podataka potrebnih za popunjavanje baze podataka su energetska bilanca (proizvodnja i uvoz primarne energije, potrošnja energije u kućanstvima), statistički podaci, subjekti poput Industrije nafte INA koja daje podatke o cijenama derivata nafte i troškovima uvoza i ostali izvori podataka (razne studije i baze podataka).

The sources of the data required for completing the data base are the energy balance (the production and import of primary energy, energy consumption in households), statistical data, subjects such as Industrija Nafte (INA) which provide data on the prices of oil derivatives and import costs, and other sources of data (various studies and databases).



Slika 5 Ulazni podaci za modeliranje nacionalnog energetskog sustava modelom MARKAL

Figure 5 Input data for national energy system MARKAL model

Ovisno o namjeni model MARKAL može se koristiti za planiranje energetskog sustava kao samostalni model ili u kombinaciji s više drugih modela (za planiranje pojedinih energetskih podsektora). U prvom primjeru model MARKAL metodom najmanjeg troška optimizira promatrani energetski sustav u cjelini. U slučaju potrebnih analiza utjecaja jednog podsektora (napr. elektroenergetskog) na zbivanja u ostalim podsektorima sustava (napr. plinskom), model MARKAL može se primijeniti u kombinaciji s više različitih modela, kako je prikazano na slici 5. Na ovaj način rezultati analize dodatnih modela služe kao ulazni podaci za model MARKAL. U prikazanom primjeru podaci potrebni za kreiranje scenarija pogona elektroenergetskih postrojenja dobivaju se iz rezultata modela WASP, a podaci o specifičnim investicijama prijenosnih i distribucijskih mreža električne energije prilagodbom rezultata modela MEXICO, TOKSWin i PRAO. Zbog potrebe postavljanja dodatnih ograničenja (s obzirom na način rada linearnog modela MARKAL) neki sektori potrošnje energije (poput kućanstava i prometa) zahtijevaju posebnu analizu simulacijskim modelom ENPEP.

6 ZAKLJUČAK

Osnovna zadaća energetske politike svake zemlje su sigurnost dobave energije, sigurna opskrba potrošača energijom i isporuka energije uz što niže troškove. To je osobito važno za Republiku Hrvatsku zbog gospodarskih i političko-strateških razloga (zemljopisnog oblika, geopolitičkog položaja, ratnog iskustva), koji nameću potrebu takvog planiranja izvora i postrojenja za pretvorbu energije, koji će smanjiti rizike u opskrbi potrošača. Uz sigurnost opskrbe energijom usko je povezana i potreba za diverzifikacijom energetskih izvora u smislu smanjenja ili potpunog otklanjanja energetske

Depending on the purpose, the MARKAL model can be used for the planning of an energy system as an independent model or in combination with several other models (for the planning of individual energy sub-sectors). In the first example, the MARKAL model optimizes the studied energy system as a whole, using the least-cost method. In the event of the need to analyze the impact of an individual subsector (for example, electricity) on events in other sub-sectors of the system (for example, gas), the MARKAL model may be applied in combination with several different models, as shown in Figure 5. In this way, the results of the analyses of additional models serve as input data for the MARKAL model. In the example presented, the data needed for creating the scenario of an electric power plant operation are obtained from the results of the WASP model, and data on specific investments in the electricity transport and distribution networks are obtained by adapting the results from the MEXICO, TOKSWin and PRAO models. Due to the requirements imposed by additional constraints (due to the manner in which the linear MARKAL model works), some energy consumption sectors (such as households and transport) require separate analysis using the ENPEP simulation model.

6 CONCLUSION

The basic tasks of the energy policy of every country are the secure procurement of energy, secure energy supply for consumers and the delivery of energy with the minimum expenditures. This is particularly important for the Republic of Croatia, due to economic and political-strategic reasons (geographical configuration, geopolitical position, war experience), which impose the need for such planned energy sources and energy transformation plants, that will reduce the risks in the consumer supply. The security of the energy supply is also closely connected with the need for ovisnosti o samo jednom izvoru energije. Takve i slične probleme moguće je u potpunosti analizirati samo primjenom odgovarajućih modela za planiranje energetskog sustava.

Zbog složenosti energetskog sustava ne postoji idealni model za njegovo planiranje. Osim toga, nužno je povezivanje više različitih modela, koji mogu detaljno analizirati pojedine dijelove energetskog sustava poput proizvodnje električne energije ili prijenosne i distribucijske mreže električne energije, s modelom koji iste dijelove prikazuje manje detaljno, ali ima mogućnost dodatnih analiza (račun emisije stakleničkih plinova ili prikazivanja mjera energetske učinkovitosti). Ne postoji problem koji se ne može analizirati primjenom modela za planiranje. Jedino ograničenje je dostupnost podataka, a odabir modela za planiranje ovisi o vrsti promatranog problema.

Zbog analize zajedničkog tržišta energije zemalja jugoistočne Europe, osim planiranja nacionalnog energetskog sustava Republike Hrvatske, javlja se potreba širenja područja planiranja s nacionalnog na regionalno u smislu sagledavanja više međusobno povezanih nacionalnih sustava. Na isti način moguća je i analiza više nacionalnih sustava modelom trgovine emisijama. Predmet modelske analize mogu biti i teritorijalni segmenti unutar nacionalnog energetskog sustava poput županije, otoka ili grada.

the diversification of energy sources, in the sense of reducing or entirely eliminating energy dependence upon only one energy source. Such problems can only be completely analyzed through the application of suitable planning models.

Due to the complexity of an energy system, there is no ideal model for planning one. Moreover, it is necessary to link several different models, which can analyze individual parts of an energy system in detail such as electricity production or the electricity transport and distribution networks, with a model that represents the same parts in less detail but provides the possibility of further analyses (calculation of greenhouse gas emissions or representation of energy efficiency measures). There is no problem that cannot be analyzed using planning models. The only constraint is the availability of data, and the selection of a planning model depends on the types of problems considered.

Due to analysis of the common energy market of the countries of South Eastern Europe, in addition to the planning of the national energy system of the Republic of Croatia, there is also a need for expanding the planning area from the national to the regional levels for the coverage of several mutually linked national systems. The analysis of several national systems can be performed in the same manner using the emission trading model. Territorial segments within the national energy system such as counties, islands or cities can also be subjected to model analysis.

LITERATURA / REFERENCES

[1] KAHEN, G., Integrating Energy Planning and Techno-Economic Development: A Solid Basis for the Assesment and Transfer of Energy Technology to Developing Countries, The First Joint International Symposium Energy Models for Policy and Planning, London Business School, London, 1995

[2] NYSTROM, I., Exploring the Treatment of Energy Demand in Energy Systems Engineering Modeling, Thesis for the degree of Doctor of Philosophy, Chalmers University of Technology, Department of Energy Conversion, Goteborg, Sweden, 2001

[3] JALAL, A.I., Energy Policy Analysis and Strategies – Concepts and procedures, College on Evaluation of Energy Technologies and Policies for Implementation of Agenda 21, IAEA International Centre for Theoretical Physics Abdus Salam, Italy, Trieste, 2003

[4] BOŽIĆ, H., Unapređenje modeliranja dugoročnog planiranja razvoja energetskog sustava, doktorska disertacija, Sveučilište u Zagrebu, Fakultet elektrotehnike i računarstva, Zagreb, 2005.

[5] CONZELMANN, G., Overview of the Energy and Power Evaluation Programme (ENPEP), Regional Training Course on the ENPEP as an IAEA Tool for GHG Abatement Cost Studies, Ukraine, Kiev, 2001

[6] VAN BEECK, N., Classification of Energy Models, Tilburg University and Eindhoven University of Technology, Netherland, 1999

[7] REUTER, A., KUHNER, R., WOHLGEMUTH, N., Energy Models - Methods and Trends, 5th Forum HED, Zagreb, 1996

[8] CHIANG, A.C., Osnovne metode matematičke ekonomije, MATE, Zagreb, 1994.

[9] CAPROS, P., Integrated Economy/Energy/Environment Models, International Symposium on Electricity, Health and the Environment, IAEA, Vienna, 1995

[10] GOLDSTEIN, G. et al., Energy Planning and the Development of Carbon Mitigation Strategies - Using the MARKAL Family of Models, International Resource Group, Washington, D.C., 1999

Uredništvo primilo rukopis:
2006-09-25

Prihvaćeno:
2006-10-06

Manuscript received on:
2006-09-25

Accepted on:
2006-10-06