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SADRŽAJ

CONTENTS

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UREĐIVAČKA POLITIKA

Časopis Energija znanstveni je i stručni časopis s dugom tradicijom više od 50 godina. Pokriva područje elektroprivredne djelatnosti i energetike. Časopis Energija objavljuje izvorne znanstvene i stručne članke širokoga područja interesa, od specifičnih tehničkih problema do globalnih analiza procesa u području energetike.

U vrlo širokom spektru tema vezanih za funkcioniranje elektroprivredne djelatnosti i općenito energetike u tržišnim uvjetima i općoj globalizaciji, časopis ima poseban interes za specifične okolnosti ostvarivanja tih procesa u Hrvatskoj i njezinu regionalnom okruženju. Funkcioniranje i razvoj elektroenergetskih sustava u središnjoj i jugoistočnoj Europi, a posljedično i u Hrvatskoj, opterećeno je mnogobrojnim tehničko-tehnološkim, ekonomskim, pravnim i organizacijskim problemima. Namjera je časopisa da postane znanstvena i stručna tribina na kojoj će se kritički i konstruktivno elaborirati navedena problematika i ponuditi rješenja.

Časopis je posebno zainteresiran za sljedeću tematiku: opća energetika, tehnologije za proizvodnju električne energije, obnovljivi izvori i zaštita okoliša; korištenje i razvoj energetske opreme i sustava; funkcioniranje elektroenergetskoga sustava u tržišnim uvjetima poslovanja; izgradnja elektroenergetskih objekata i postrojenja; informacijski sustavi i telekomunikacije; restrukturiranje i privatizacija, reinženjering poslovnih procesa; trgovanje i opskrba električnom energijom, odnosi s kupcima; upravljanje znanjem i obrazovanje; europska i regionalna regulativa, inicijative i suradnja.

Stranice časopisa podjednako su otvorene iskusnim i mladim autorima, te autorima iz Hrvatske i inozemstva. Takva zastupljenost autora osigurava znanje i mudrost, inventivnost i hrabrost, te pluralizam ideja koje će čitatelji časopisa, vjerujemo, cijeniti i znati dobro iskoristiti u svojem profesionalnom radu.

EDITORIAL POLICY

The journal Energy is a scientific and professional journal with more than a 50-year tradition. Covering the areas of the electricity industry and energy sector, the journal Energy publishes original scientific and professional articles with a wide area of interests, from specific technical problems to global analyses of processes in the energy sector.

Among the very broad range of topics relating to the functioning of the electricity industry and the energy sector in general in a competitive and globalizing environment, the Journal has special interest in the specific circumstances in which these processes unfold in Croatia and the region. The functioning and development of electricity systems in Central and South East Europe, consequently in Croatia too, is burdened with numerous engineering, economic, legal and organizational problems. The intention of the Journal is to become a scientific and professional forum where these problems will be critically and constructively elaborated and where solutions will be offered.

The Journal is especially interested in the following topics: energy sector in general, electricity production technologies, renewable sources and environmental protection; use and development of energy equipment and systems; functioning of the electricity system in competitive market conditions; construction of electric power facilities and plants; information systems and telecommunications; restructuring and privatization, re-engineering of business processes; electricity trade and supply, customer relations, knowledge management and training; European and regional legislation, initiatives and cooperation.

The pages of the Journal are equally open to experienced and young authors, from Croatia and abroad. Such representation of authors provides knowledge and wisdom, inventiveness and courage as well as pluralism of ideas which we believe the readers of the Journal will appreciate and know how to put to good use in their professional work.

UVOD
INTRODUCTION

Poštovani čitatelji!

Pred Vama je drugi broj časopisa Energija u 2009. godini. Nakon tema vezanih uz sigurnost dobave kao i opskrbe kupaca energijom odnosno različitim energentima, najzanimljivije su teme vezane uz smanjenje utjecaja na okoliš energetskih objekata kao i teme vezane uz tržište energenata. Tako u ovom broju časopisa Energija donosimo članke vezane uz razvoj i primjenu tehnologija koje u određenoj mjeri smanjuju emisiju stakleničkih plinova kao i neke pojavne oblike vezane uz tržište električne energije. Ne treba posebno naglašavati kako je ovo razdoblje označeno smanjenjem investicija u energetski sektor pa je to upravo prigoda da se malo više bavimo analizama različitih aspekata energetskog sektora i u tom smislu vas pozivamo da nam se pridružite svojim radovima na ovim i sličnim temama.

U ovom broju časopisa Energija objavljujemo vrlo zanimljive članke iz različitih područja, od energetskih do specijalističkih područja elektrotehnike:

— Tehnologije hvatanja i spremanja ugljikovog dioksida u elektroenergetskom sektoru – pregled relevantnih stanja,
— Anomalija cijene na spot tržištu električne energije europske burze energije EEX (Leipzig),
— Analiza velikog kvara u transformatorskoj stanici na otoku Kreti,
— Estimacija kuta opterećenja sinkronog generatora dinamičkim neuronskim mrežama,
— Održavanje nazivnih performansi plinske turbine pri povišenim temperaturama okoliša.

U prvom članku daje se prikaz stanja razvoja i perspektive u jednom vrlo zanimljivom području koje se odnosi na spremanje ugljikovog dioksida. Zaštita okoliša koja se odnosi na smanjenja emisije stakleničkih plinova postiže određene rezultate i to prvenstveno na području povećanje energetske učinkovitosti. Pokazuje se ipak da to neće biti dovoljno pa je nužno razviti i neke druge tehnologije koje na određeni način smanjuju emitiranje ugljikovog dioksida u atmosferu. Tehnologije hvatanja, izdvajanja i spremanja ugljikovog dioksida sačinjavaju tako drugu obećavajući opciju koja može drastično reducirati ove emisije. Značajan napredak, napravljen u zadnjih desetak godina, omogućio je da se neka kompleksna tehnološka rješenja nalaze vrlo blizu komercijalne primjene. Ovaj članak omogućava kratak pregled relevantnog stanja tehnologija hvatanja, izdvajanja, transport i skladištenja ugljikovog dioksida koje će možda za dva desetljeća biti u širokoj primjeni u elektroenergetskom sektoru.

Drugi članak u ovom broju časopisa Energija opisuje jednu krajnje zanimljivu pojavu koja se dogodila ili je bolje reći događa na tržištu električne energije. Europska burza energije EEX postala je, uz Nord Pool u nordijskim zemljama, najznačajnija burza energije u kontinentalnoj Europi. U radu je prikazana i razmatrana pojava negativne cijene na spot tržištu električne energije na EEX-u krajem prosinca 2008. godine. Negativna cijena, kada je predviđena i dopu-

Dear readers!

Before you is the second edition of Energija for the year 2009. After the themes related to supply security as well as to customers' supply with energy, that is, different energy sources, the most interesting themes are related to reduced environment impact of energy objects as well as the themes related to the energy sources market. Therefore, in this issue of Energija, we present articles related to the development and application of the technologies which, to a certain extent, reduce greenhouse gas emission as well as certain events related to the electricity market. It need not be especially stressed that this period is marked by decreased investment into the energy sector so this is the right occasion to address more seriously the analyses of different aspects of the energy sector and for that purpose, we invite you to join us with your works addressing these and similar issues.

In this issue of Energija, we present very interesting articles from various fields, from the energy-related to specialist electrical engineering fields:

— Carbon dioxide capture and storage technologies in the electric power sector – overview of the relevant situations,
— Price anomaly on the European Energy Exchange (Leipzig) electricity market,
— Analysis of a major failure of the transformer unit on the island of Crete,
— Load angle estimation of a synchronous generator using dynamical neuron networks,
— Maintaining declared performance in gas turbines during increased ambient temperatures.

The first article presents an overview of the situation of development and the perspectives in a very interesting field related to carbon dioxide capture. Environment protection regarding the reduction of greenhouse gas emission achieves certain results and that being primarily in the area of increased energy efficiency. However, it comes out nevertheless that this will not suffice so it is necessary to develop also some other technologies which reduce the carbon dioxide emission into the atmosphere to a certain extent. Carbon dioxide capture, isolation and storage technologies thus constitute the second, promising option which can drastically reduce these emissions. Significant progress accomplished in the last ten years enabled some complex technological solutions to come close to commercial application. This article enables a short overview of the relevant situation in carbon dioxide capture, isolation, transport and storage which could be widely used in the electric power sector two decades from now.

The second article of this issue of Energija describes one extremely interesting occurrence which happened, or better said, is happening on the electricity market. The EEX (European Energy Exchange) has become, along with Nord Pool in Nordic countries, the most significant energy exchange in continental Europe. The work also shows and deliberates on the occurrence of negative prices on the EEX electricity spot market at the end of December 2008. The negative price, when predicted and allowed at the energy exchange, mirrors the situštena na burzi energije, odražava situaciju na tržištu u kojoj je ponuda značajno nadmašila potražnju. Članak je posebno zanimljiv jer daje i analizu uzroka koji su doveli do ovako neobične pojave. Ova pojava je međutim neobična jer se negativna cijena neke druge robe na tržištu praktički ne može pojaviti pa se i po tomu tržište električne energije izdvaja od uobičajenog tržišta ostalih roba.

U trećem, vrlo zanimljivom članku od naših sada već starih suradnika iz Grčke, profesora Papazoglou-a i suradnika, daje se jedan potpun prikaz događanja vezanih uz veliki kvar u elektroenergetskom sustavu Krete koji je za posljedicu imao veliku štetu na TS Iraklio 3. Problem je počeo zbog kvara na srednjem naponu u transformatorskoj stanici pa kako se kvar nije uklonio na vrijeme, došlo je do velikih struja kratkog spoja tijekom 16 minuta, požara na opremi i velike štete na visokom i srednjem naponu kao i razvodima istosmjerne struje u transformatorskoj stanici. U članku se daje opis slijeda događaja tog kvara s podrobnom analizom slijeda događanja. Rezultat svega su zaključci od praktične važnosti kao i preporuke u odnosu na poboljšanja u hardverskom i zaštitnom sustavu i dostupnoj tehničkoj potpori, koje mogu biti presudne za izbjegavanje i/ili ograničavanje štete kod budućih kvarova.

U četvrtom članku se daje vrlo zanimljiva analiza i modeliranje estimacije kuta opterećenja generatora. Kut opterećenja sinkronog generatora u radu na elektroenergetski sustav (EES) pogonska je veličina koja daje praktički direktni podatak o položaju radne točke generatora u odnosu na granicu stabilnosti. Rad EES-a karakteriziraju velike promjene pogonskog režima rada sinkronog generatora, tako da prijelaz iz jednog u drugo ustaljeno pogonsko stanje najčešće prate značajne dinamičke promjene kuta opterećenja. U članku je definiran postupak estimacije kuta opterećenja sinkronog generatora u radu na elektroenergetski sustav zasnovanog na dinamičkim neuronskim mrežama. Usporedbom rezultata dobivenih primjenom definiranog postupka estimacije kuta opterećenja, s rezultatima dobivenim mjerenjem, pokazana je primjenjivost predloženog estimacijskog postupka zasnovanog na dinamičkim neuronskim mrežama.

U petom članku je prikazana analiza utjecaja hlađenja ulaznog zraka u plinsku turbinu na njene performanse. Klasični proces plinske turbine karakterizira kompresija zraka iz okoline, koji se u komorama izgaranja zagrijava izgaranjem goriva te tako stvoreni dimni plinovi ekspandiraju u turbini i proizvode mehanički rad. Performanse plinske turbine ovise o svemu što mijenja gustoću i/ili maseni protok zraka na usisu kompresora. Najočitije promjene u performansama plinske turbine su smanjenje snage i povećanje specifične potrošnje goriva s porastom temperature okoliša, pri čemu nastaju značajna odstupanja od vrijednosti garantiranih (i postignutih) pri ISO uvjetima. Hlađenjem zraka na usisu kompresora pri povišenim temperaturama okoliša postiže se povećanje masenog protoka i kompresijskog omjera, te se sprječava smanjenje snage i povećanje specifične potrošnje goriva. U radu je na primjeru turbine GE-PG6101FA prikazana ovisnost o okolišnim klimatskim uvjetima, te način na koji se ta ovisnost može smanjiti ili otkloniti.

Članke u ovom broju časopisa Energija potpisuju autori iz sveučilišne zajednice, ali i iz prakse, što je, sasvim sigurno, rezultiralo i kvalitetnim člancima.

Glavni urednik:
Mr. sc. Goran Slipac

ation on the market in which the offer has significantly exceeded the demand. The article is especially interesting because it provides the analysis of the causes which brought about such an unusual occurrence. This occurrence is however unusual because a negative price of some other goods on the market practically cannot occur and this is another reason for the specificity of the electricity market in relation to the standard market of other goods.

The third, very interesting article written by our established associates from Greece, professor Papazoglou and associates, gives a full overview of the events related to the major failure of the electrical power system of Crete the consequence of which was major damage on the TS Iraklio 3. The problem began due to a failure on the middle voltage of the transformer station, and then, as the failure was not repaired on time, extensive short circuit currents occurred in the duration of 16 minutes, fire to the equipment and significant damage to the high and middle voltages as well as to the DC power distribution in the transformer station. The article provides a description of the line of events of that failure with a detailed analysis of the line of events. All of the above yields conclusions of practical importance as well as recommendations regarding the improvements in the hardware and protective system and the available technical support which could be crucial for the evasion and/or limitation of damage at future failures.

The fourth article gives a very interesting analysis and modelling of the angle estimation of the generator loading. The loading of the synchronous generator in operation on the electric power system (EPS) is a drive-dimension which provides virtually direct information on the position of the generator's operative point in relation to the stability limit. The EPS's operation is characterized by significant changes in the operative regime of the synchronous generator operation, so that the transition from one operative state to another is usually followed by significant dynamic changes of the load angle. The article defines the procedure of the operative synchronous generator load angle estimation on the electrical power system based on dynamic neuron networks. The comparison of the results obtained by the application of the defined load angle estimation procedure with the results obtained by measurements indicates the applicability of the suggested estimation procedure based on dynamic neuron networks.

The fifth Article shows the analysis of how the cooling of air entering the gas turbine impacts its performance. The classical gas turbine process is characterized by the compression of ambient air which heats up in the combustion chambers by fuel combustion and the flue gases generated in such way expand in the turbine and produce mechanical operation. The performances of the gas turbine depend on everything that changes the density and/or air mass flow rate at the compressor suction point. The most significant changes in the gas turbine performance are reduced power and increased fuel consumption following higher ambient temperatures, whereat significant deviations occur from the values guaranteed (and achieved) at ISO conditions. The cooling of air at the compressor suction hole at increased ambient temperatures provides for an increased mass flow rate and compression ratio and prevention of reduced power and increase of specific fuel consumption. The work uses the example of the GE-PG6101FA turbine to depict the dependence on ambient climatic conditions and the way in which such dependence can be reduced or removed.

The articles in this issue of Energija were written by the authors both from the academic community and from practice which surely resulted in articles of high quality as well.

Editor-in-chief.
Goran Slipac, MSc

TEHNOLOGIJE HVATANJA I SPREMANJA UGLJIKOVOG DIOKSIDA U ELEKTROENERGETSKOM SEKTORU – PREGLED RELEVANTNOG STANJA

CARBON DIOXIDE CAPTURE AND STORAGE TECHNOLOGIES IN THE ELECTRIC POWER SECTOR – OVERVIEW OF THE RELEVANT SITUATION

Branimir Loš, Zagreb, Hrvatska

U dolazećih pola stoljeća fosilna goriva će biti ekstenzivno korištena, a emisija CO2 rasti, ukoliko ne bude provedena u djelo nova energetska politika. Postoje brojne opcije kojima se može reducirati emisija CO2 iz energetskih sustava. One uključuju poboljšavanje energetske efikasnosti, prijelaz na obnovljivu i nuklearnu energiju. Međutim, politika temeljena na ovim opcijama će, u najboljem slučaju, samo djelomično riješiti problem. Tehnologije hvatanja, izdvajanja i spremanja ugljikovog dioksida sačinjavaju drugu obećavajući opciju koja može drastično reducirati ove emisije. Zbog tog razloga se hvatanje, izdvajanje, transport i skladištenje ugljikovog dioksida studiraju godinama. Brojni tehnički koncepti se predlažu; često spekulativne naravi – plod apstrakcije, daleko od iskustva i prakse. Mnogi od njih iziskuju vrlo velike istraživačke i razvojne napore prije komercijalizacije. Značajan napredak, napravljen u zadnjih desetak godina, omogućio je da se neka kompleksna tehnološka rješenja nalaze vrlo blizu komercijalne primjene. Ovaj članak omogućava kratak pregled relevantnog stanja tehnologija hvatanja, izdvajanja, transport i skladištenja ugljikovog dioksida koje će možda za dva desetljeća biti u širokoj primjeni u elektroenergetskom sektoru.

In the next half century, fossil fuels will be used extensively and the CO_2 emission will increase unless new energy policies are put through. There are numerous possibilities for the reduction of the CO_2 emission from the energy systems. These include the improvement of energetic efficiency and the switch to renewable and nuclear energy. However, the policy based on these options will, in the best case, solve the problem only partially. Carbon dioxide capture, isolation and storage technologies constitute the second, promising option which can drastically reduce these emissions. Because of that, carbon dioxide capture, isolation, transport and storage have been studied for years. Numerous concepts have been proposed, often of speculative nature- products of abstraction, far from experience and practice. Many of these require great research and developmental efforts before commercialization. Significant progress accomplished in the last ten years enabled some complex technological solutions to come close to commercial application. This article enables a short overview of the relevant situation in carbon dioxide capture, isolation, transport and storage, which could be widely used in the electric power sector two decades from now.

Ključne riječi: demonstracijska postrojenja; efikasnost; istraživanje; nadzor; neizvjesnost; planiranje; primjena; rizici; troškovi; značajke

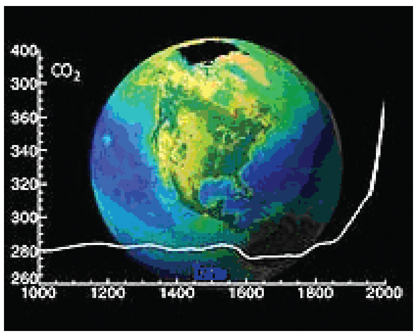
Key words: application; costs; demonstration plants; efficiency; planning; properties; research; risks; supervision; uncertainty

1 UVOD

Intenzivni razvitak industrije datira od sredine 19. stoljeća. Razvitak prati povećanje razine koncentracije ugljikovog dioksida u atmosferi sa 280 ppmí (partes per milion mol) na skoro 370 ppmí [1] . Nema točnog odgovora, kolika je granična koncentracija nakon koje će negativne i nepovratne klimatske promjene prouzročiti u konačnici propadanje ljudske civilizacije. Struka smatra da je ona bliže 450 ppmí nego 750 ppmí. Bez ikakvih mjera za smanjenje koncentracije ugljikovog dioksida u atmosferi bit će ga oko 900 ppmí 2100. godine. Na slici 1 je prikazan porast koncentracije CO_2 u atmosferi od 1000. do 2000. godine.

1 INTRODUCTION

Intense industry development dates back to the mid-19th century.The development was accompanied by an increased concentration of carbon dioxide in the atmosphere from 280 ppmí to almost 370 ppmí [1] (ppmí – partes per million mol). There is no correct answer as to the amount of the cut-off concentration beyond which negative and irrecoverable climatic changes will finally cause the destruction of human civilization. The profession believes that it is closer to 450 ppmí than to 750 ppmí. Without any measures for the reduction of the carbon dioxide concentration in the atmosphere, in the year 2100, it will amount to about 900 ppmí. Figure 1 shows the increase of the CO_2 concentration in the atmosphere from 1000 to 2000.



Slika 1 — Promjena koncentracija (ppmí) ugljikovog dioksida u atmosferi u zadnjih tisuću godina
Figure 1 — Change of carbon dioxide concentrations (ppmí) in the atmosphere in the last thousand years.

Stanje je alarmantno jer nije izglednija masovnija uporaba tehnologija za hvatanje, izdvajanje, transport i skladišenje (u nastavku HITS CO_2) u idućih 15 godina. Pretpostavlja se da će emisija ugljikovog dioksida porasti na 30 Gt CO_2 te da će se od 3 Gt CO_2 do optimističkih 76 Gt CO_2[2] moći trajno zbrinuti u geološke naslage ispod zemlje. Sustav HITS CO_2, proizvednog tijekom uporabe fosilnih goriva, može se izgraditi na postojećim tehnologijama. Sve aktivnosti su već pojedinačno implementirane u određenim aplikacijama na komercijalnoj razmjeri. Danas, niti jedan HITS CO_2 sustav u svijetu ne djeluje na komercijalnim postrojenjima za proizvodnju električne energije.

Proizvodnja električne energije ostvarena loženjem fosilnih goriva je odgovorna za više od 30 % ukupne današnje emisije CO_2. Uspoređujući druge opcije ublažavanja emisije CO_2 u elektroenergetskom sektoru, HITS CO_2 treba manja restrukturiranja sustava energetske dobave, pa čak i u samo nekoliko izvedenih projekata se može postići značajan utjecaj na emisije CO_2 na državnoj ili regionalnoj razini.

The situation is alarming because a more extensive use of capture, isolation, transport and storage technologies (hereinafter: CITS CO2) in the next 15 years is not probable. The assumption is that carbon dioxide emission will increase to 30 Gt CO_2 and that from 3 Gt CO_2 up to the optimistic amount of 76 Gt CO_2 [2] could be permanently put into geological underground deposits. The CITS CO_2 system, produced during the use of fossil fuels, can be built on existing technologies. All the activities have already been separately implemented in certain applications at commercial levels. Today, none of the CITS CO_2 systems in the world are applied on commercial plants for the production of electricity.

Electricity production realized by the firing of fossil fuels is accountable for more than 30 % of today's total CO_2 emission. By comparing other options for CO_2 emission amelioration in the electric power sector, the CITS CO_2 requires less restructuring of the energy supply system, and therefore in only a few executed projects a significant impact on CO_2 emission can be achieved at the national or regional level.

Važno je naglasiti da industrijski procesi generiraju oko 23 % emisije CO_2 u svijetu, a moguće je realizirati HITS CO_2 tijekom proizvodnje željeza, cementa, kemikalija i papira. U nekim slučajevima troškovi HITS-a mogu biti i niži nego u proizvodnji električne energije. Problem je što su jedinični izvori emisije manji od elektroenergetskih, tako da je njihovo povezivanje glede transporta CO_2 složenije i skuplje.

U članku je dan pregled razvoja značajnih tehnoloških rješenja na kojima je zasnovan kompleksan sustav za hvatanje, izdvajanje, transport i skladištenja CO_2. Kvantificirane su njegove tehničke značajke, za koje tek treba razviti odgovarajući globalni sustav poslovanja. Međunarodna agencija za energiju (IEA) je pokrenula 1991. godine provedbu Programa razvoja i istraživanja stakleničkih plinova (u nastavku IEA GHG). IEA GHG je kroz međunarodnu suradnju, 26 zemalja članica i Europske (EU) komisije, inicirala razvoj tehnologija sposobnih za postizanje velikog smanjenja emisije stakleničkih plinova. IEA značajno organizacijski i financijski pomaže provedbu Programa, utječe na dinamiku napredovanja niza projekata i objektivno godišnje izvješćuje o njihovom napredovanju.

2 SVOJSTVA UGLJIKOVOG DIOKSIDA

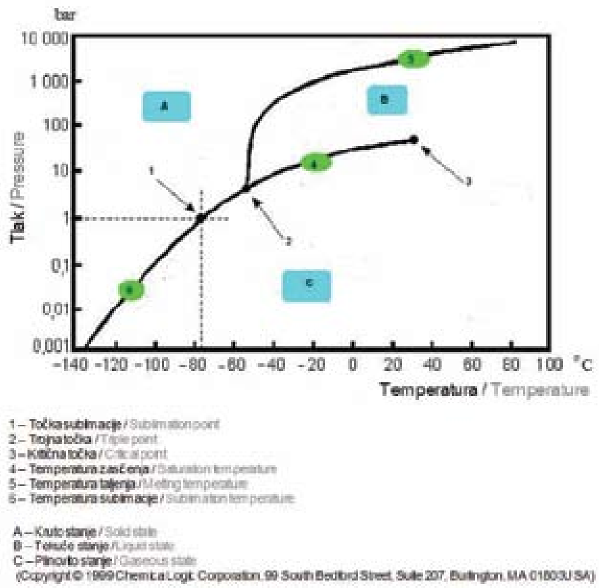
Pri normalnoj temperaturi i tlaku je ugljikov dioksid u plinovitom stanju. Fizičko stanje varira s temperaturom i tlakom, kako je prikazano na slici 2. Pri niskim temperaturama CO_2 je u krutom stanju, zagrijavanjem se, ako je tlak ispod 5,1 bar, iz krutog stanja izravno sublimira u plinovito stanje. Na međutemperaturama (između temperature trojne točke –56,5 °C,i temperature kritične točke od 31,1 °C), uz uklanjanje proizvedene topline CO_2 može prelaziti od pare u tekuće stanje komprimiranjem na odgovarajućem tlaku ukapljivanja. Pri temperaturama višim od 31,1 °C (ukoliko je tlak viši od tlaka u kritičnoj točci, 73,9 °C), za CO_2 se kaže da je u nadkritičnom stanju u kojem se ponaša kao plin; pod doista visokim tlakom gustoća plina može veoma varirati približavajući se ili čak biti veća od gustoće tekuće vode. Ovo je značajan aspekt ponašanja CO_2 i osobito je značajan za njegovo odlaganje. Toplina se oslobađa ili apsorbira pri svakoj promjeni faza/stanja preko granice kruto-plinovito i tekuće-plinovito. Međutim, fazne promjene iz nadkritičnog stanja u tekuće ili iz nadkritičnog stanja u plinovito ne zahtijevaju ili oslobađaju toplinu. Ovo svojstvo je korisno za projektiranje uređaja za komprimiranje. Značajnija fizička svojstva CO_2 su prikazana u tablici 1.

It is important to point out that industrial processes generate about 23 % of CO_2 emissions in the world, and it is possible to realize CITS CO_2 in the course of the production of iron, cement, chemicals and paper. In certain cases, the CITS costs can be even lower than those in electricity production. The problem is that unit emission sources are smaller than the electrical energy sources, therefore, their interconnection as regards CO_2 transport is more complex and more expensive.

The article depicts the overview of the development of significant technological solutions on which the complex system for the capture, isolation, transport and storage of CO_2 is based. Its technical properties are quantified and for these an adequate global business operation system still needs to be developed. In 1991, the International Energy Agency (IEA) launched the implementation of the Greenhouse Gas Research and Development Programme (hereinafter: IEA GHG). By virtue of international cooperation of 16 EU member states and the European Commission, the IEA GHG initiated the development of technologies capable of achieving significant reduction of greenhouse gas emissions. The IEA significantly supports the implementation of the Programme organizationally and financially, it impacts the dynamics of the progress of a number of projects and issues objective annual reports on their progress.

2 CARBON DIOXIDE FEATURES

At a normal temperature and pressure, carbon dioxide is in gaseous state. Its physical state varies depending on the temperature and the pressure, as shown in Figure 2. At low temperatures, CO_2 is in gaseous state, and, when heated, if the pressure is lower than 5,1 bar, from solid state it directly sublimates into gaseous state. At inter-temperatures (between the triple point temperature of –56,5 °C and the critical point temperature of 31,1 °C), with the removal of the generated heat, CO_2 can change from gaseous to liquid state by compression at the adequate liquification pressure. At temperatures higher than 31,1 °C (if the pressure is higher than the pressure at the critical point, 73,9 °C), CO_2 is said to be in supercritical state in which it behaves as gas; at a very high pressure, gas density may vary significantly and come close to or even higher than liquid water density. This is an important aspect of CO_2 behaviour and it is especially important for its disposal. Heat is released or absorbed at any change of phase/state over the solid-gaseous and liquid-gaseous boundary. However, phase changes from supercritical state to liquid or from supercritical state to gaseous do not require or release heat. This feature is useful for the design of compression devices. Key physical features of $CO_2$are shown in



Slika 2 — Fazni dijagram za CO_2
Figure 2 — Phase diagram for CO_2

Tablica 1 – Fizička svojstva ugljikovog dioksida
Table 1 - Carbon dioxide physical properties

Svojstvo / Property	Vrijednost / Value
Molekularna težina / Molecular weight	44,01
Kritična temperatura / Critical temperature, °C	31,1
Kritični tlak / Critical pressure, bar	73,9
Kritična gustoća / Critical density, kg/m³	467
Temperatura u trojnoj točci / Triple point temperature, °C	– 56,5
Tlak u trojnoj točci / Triple point pressure, bar	5,18
Točka ključanja (sublimacije) na / Boiling (sublimation) point at 1,013 bar, °C	– 78,5
Plinovita faza / Gaseous phase	
Specifična gustoća u točki ključanja / Specific density at the boiling point (1,013 bar), kg/m³	2,814
Specifična gustoće STP / Specific density STP, kg/m³	1,976
Specifični volumen STP / Specific volume STP, kg/m³	0,506
Viskozitet (STP) / Viscosity (STP), µPa · s	13,72
Topivost u vodi (STP) / Solubility in water (STP), vol/vol	1,716
Entalpija (STP) / Enthalpy (STP), kJ/mol	21,34
Tekuće stanje / Liquid state	
Tlak pare / Vapour pressure (pri / at 20 °C), bar	58,5
Gustoća tekuće faze / Liquid phase density (–20 °Ci / and 19,9 bar), kg/m³	1032
Viskozitet (STP) / Viscosity (STP), µPa · s	99
Kruto stanje / Solid state	
Gustoća CO_2 u točki zaleđivanja / CO_2 density at freezing point, kg/m³	1562
Latentna toplina isparavanja / Latent vaporization heat (1,013 bar u točki sublimacije / at sublimation point), kJ/kg	571,1

Napomena: STP standardna temperatura i tlak, jednaki 0 °C i 1,013 bar. Izvor: Air Liquid gas data table (Kirk-Otmer, Encyclopedia of Chemical Technology 1985)
Remark: STP standard temperature and pressure, equal to 0 °C and 1,013 barSource: Air Liquid gas data table (Kirk-Ot-hmer, Encyclopedia of Chemical Technology 1985)

3 TEHNOLOGIJE HVATANJA I IZDVAJANJA CO_2

Tehnologije hvatanja i izdvajanja CO_2 (u nastavku HICO2) se temelje na: apsorpciji (kemijska i fizička), adsorpciji, kriogenim postupcima i membranama. Trenutačno su u pogonu apsorpcioni reaktori dnevnog kapaciteta manjeg od 1 000 t CO_2. Klasični termoenergetski blok električne snage od 250 MW ložen kamenim ugljenom dnevno emitira oko 4 500 t CO_2, a kombi blok ložen prirodnim plinom jednake snage oko 2 150 t CO_2. To znači da bi se za veće proizvodne jedinice, postrojenje za HI moralo izgraditi od većeg broja manjih jedinica, to bi za posljedicu imalo povećana ulaganja, veliku vlastitu potrošnju i dvojbenu sigurnost pogona. Stručni krugovi očekuju da će bar jedna od tri glavne skupine tehnoloških postupaka, prikazane na slici 3, moći biti komercijalno primijenjena, u sljedećih deset do petnaest godina kod velikih proizvodnih jedinica u elektroenergetskom i industrijskom sektoru za hvatanje i izdvajanje CO_2 iz fosilnih goriva [3], [4] i [5]:

- hvatanje i izdvajanje ugljikovog dioksida nakon izgaranja ($HICO_2$-NI),
- hvatanje i izdvajanje ugljikovog dioksida prije izgaranja ($HICO_2$-PI),
- hvatanje i izdvajanje ugljikovog dioksida izgaranjem u struji kisika ($HICO_2$-Ox).

Mogućnost njihove primjene se temelji na komponentama provjerenima u komercijalnom pogonu kao što su rafinacija nafte, procesuiranje prirodnog plina i proizvodnja sintetičkih goriva. Trenutačno ne postoji u pogonu termoenergetsko pokazno postrojenje s potpunim $HICO_2$, u kojem bi se mogli provjeriti tehnički i komercijalni pokazatelji poslovanja.

Svi ostali tehnološki postupci za termo-elektroenergetska postrojenja su spekulativne naravi, često utemeljeni samo na laboratorijskim opitima ili pilot postrojenjima čije specifične rezultate rada je vrlo teško generalizirati.

Trenutačno se može izgraditi i staviti u funkciju $HICO_2$ za dekarbonizaciju fosilnih goriva u proizvodnji vodika (izdvajanje prije izgaranja) ili za hvatanje i izdvajanje CO_2 iz dimnih plinova nakon nekih industrijskih procesa (izdvajanje nakon izgaranja). Poboljšanja, u praksi dokazanih tehnologija manjih jediničnih snaga, uključuju razvoj novih kemijskih i fizičkih otapala za CO_2 s ciljem smanjenja energetskih potreba procesa izdvajanja. Za novije procese, istraživanja se usmjeravaju na bolje i jeftinije membrane za postupke povećanja koncentracije CO_2, efikasniju tehnologiju razdvajanja zraka (neke opcije uključuju izgaranje u čistom kisiku), jeftinije i efikasnije gorive ćelije (za pretvaranje kemijske

3 CO_2 CAPTURE AND ISOLATION TECHNOLOGIES

CO_2 capture and isolation technologies (hereinafter CICO2) are based on: absorption (chemical and physical), adsorption, cryogenic procedures and membranes. At the moment, absorption reactors which are in operation are of daily capacity below 1000 t CO_2.The classic thermal energy block of 250 MW fired by hard coal emits about 4 500 t CO_2 daily, and the combined block fired by natural gas of equal power emits about 2 150 t CO_2. This means that for larger production units, the CI plant should be built from a larger number of smaller units which would result in significant investments, extensive own spending and uncertain safety of the plant. Expert circles expect that at least one of the three main groups of technological procedures, shown in Figure 3, could be commercially applied in the next ten to fifteen years in large production units in the electric power and industrial sector for the capturing and isolation of CO_2 from fossil fuels [3], [4] and [5]:

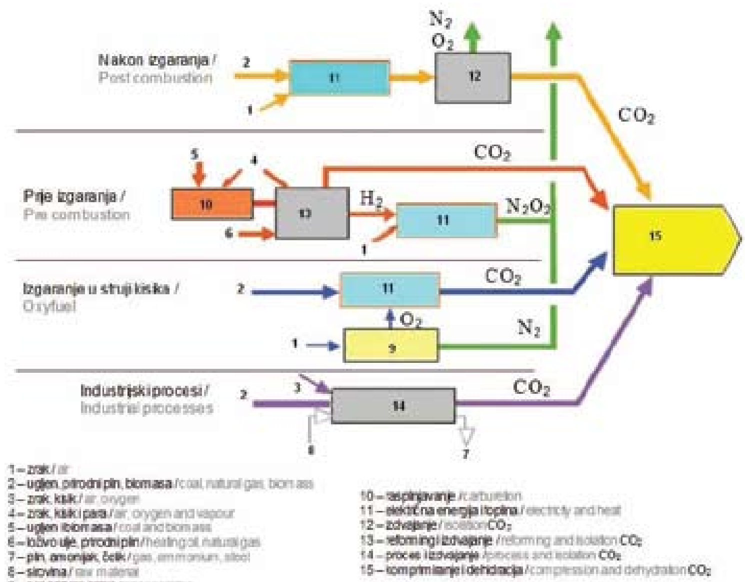
- capture and isolation of carbon dioxide after combustion ($CICO_2$-AC),
- capture and isolation of carbon dioxide before combustion ($CICO_2$-BC),
- capture and isolation of carbon dioxide by oxy-fuel ($CICO_2$-Ox),

The possibility of their application is based on the components tested in commercial plants such as oil refinery, processing of natural gas and production of synthetic fuels. At the moment, no thermal energy demonstration plant with complete $CICO_2$, in which the technical and commercial business indicators could be tested, is in operation.

All other technological procedures for thermal-electric power plants are of speculative nature, often based only on laboratory tests or pilot plants the specific results of the work of which are difficult to be generalized.

Now, a $CICO_2$ for decarbonisation of fossil fuels in hydrogen production (isolation before combustion) or for the capture and isolation of CO_2 from flue gases after certain industrial processes (isolation after combustion) can be constructed and put into operation. Improvements of technologies of smaller unit powers proven in practice include the development of new chemical and physical solvents for CO_2 with the aim to reduce energy requirements of the isolation process. For newer processes, research is focused on better and cheaper membranes for the CO_2 concentration increase processes, more efficient air separation technology (some options include combustion in pure oxygen), cheaper and more efficient combustive energije spremljene u vodiku ili metanu u električnu energiju), turbine na vodik, kemijske petlje itd. U tablici 2 prikazane su mogućnosti smanjenja emisije CO_2 iz nekih fosilnih goriva.

cells (for the transformation of chemical energy stored in hydrogen or methane into electricity), hydrogen-driven turbines, chemical loops, etc. Table 2 shows the possibilities of reduction of CO_2 emission from certain fossil fuels.



Slika 3 — Tri glavne opcije za hvatanje CO_2 iz termoelektrana

Figure 3 — Three main options for the capture of CO_2 from thermal power plants

Tablica 2 – Procjena tehnologija glede mogućnosti smanjenja emisije CO_2 [2]

Table 2 - Evaluation of technologies as regards the possibilities of reduction of CO_2 emission [2]

Procjena mogućnost tehnologija za 2020. godinu / Evaluation of technologies' possibilities for the year 2020	Ugljen / Coal	Loživo ulje / Heating oil	Prirodni plin / Natural gas
g CO_2/kWh (bez HITS/ without CITS)	900	660	330
g CO_2/kWh + HITS/CITS	108	-	54
Udio, %, uhvaćenog od emitiranog / Share, %, of captured out of the emitted	90	-	85
Dodatno gorivo za pogon HITS opreme, % od izvornog koncepta bez HITS / Additional fuel for the CITS equipment drive, % of original concept without CITS	20	-	10

Kod korištenja kamenog ugljena (tablica 3) prednost se daje tehnologiji $HICO_2$-PI, kod koje se izdvajanje obavlja u struji dimnih plinova s povećanom koncentracijom CO_2 budući da se rasplinjavanje obavlja u struji čistog kisika bez nazočnosti dušika. Nužno je naglasiti da još nije, nakon dugogodišnjih istraživanja, postignuta konkurentnost postrojenja za rasplinjavanje kamenog ugljena. Klasična tehnologija spaljivanja ugljene prašine je još uvijek bez konkurencije glede učinka, raspoloživosti, pouzdanosti i trajnosti opreme. Niti jedno postrojenje u svijetu ne rasplinjava na komercijalnoj osnovici kameni ugljen, već samo ostatke prerade nafte u rafinerijama. Izgaranje kisikom,

When using hard coal (Table 3), preference is given to the $CICO_2$-BC technology in which the isolation is performed in the flue gases current with an increased CO_2 concentration because the carburetion is performed in the pure oxygen current without the presence of nitrogen. It is important to point out that, in spite of years of research, competitiveness of the hard coal carburetion plants has not been achieved yet. Classic technology of coal dust combustion is still unparalleled as regards the effect, availability, reliability and durability of equipment. None of the world plants perform the carburetion on the hard coal commercial basis, but only on the basis of the waste from oil proce-

$HICO_2$-Ox, pokazuje dobre rezultate na jednom malom pokaznom postrojenju toplinske snage od 30 MW, ali na pitanja o životnom vijeku opreme kotlovskog postrojenja nema odgovora. Izgaranje u struji kisika, $HICO_2$-Ox, je po ocjeni struke u prednosti kod dogradnje na postojeća postrojenja budući da je potrebno izgraditi samo novo kotlovsko postrojenje; postojeće parno-turbinsko postrojenje ostaje u funkciji.

ssing in refineries. Oxyfuel, $CICO_2$-Ox, shows good results on one small demonstration plant with 30 MW (thermal), but it does not have answers as regards the life span of the boiler plant equipment. According to professional judgement, oxyfuel, $CICO_2$-Ox is in an advantageous position when it comes to upgrading of the existing plants because the only thing that is required is the construction of a new boiler plant; the existing steam-turbine plant remains in operation.

Tablica 3 – Usporedba efikasnosti i troškova hvatanja i izdvajanja CO_2 iz elektrana loženih ugljenom [5], [6] i [7]
Table 3 - Comparison of efficiency and isolation of CO_2 from the coal-fired power plants [5], [6] and [7]

Tip $HICO_2$ tehnologije / Type of $CICO_2$ technology	$HICO_2$-AC		$HICO_2$-BC		$HICO_2$-Ox + DESOx	
Izvor podataka / Information source	2003 IAE GHG		2003 IEA GHG		2002 CTH Lippendorf projekt / project	
Tip proizvodne jedinice / Production unit type	klasični / classic	+ $HICO_2$	klasični / classic	+ $HICO_2$	klasični (zrak) / classic (air)	Kisikom / oxygen + $HICO_2$
Termoelektrana na ugljen / Coal-fired thermal power plant	Prašina / Dust	Prašina / Dust	Rasplinjavanje / Carburetion	Rasplinjavanje / Carburetion	Lignit prašina / Lignite dust	Lignit prašina / Lignite dust
Jedinična snaga / Unit power, MW_e	500	362	776	676	865	681
Neto efikasnost / Net efficiency, %	46	33	43	34	43	34
Emisija / Emission CO_2, kg/MWh_e	722	148	763	142	858	69
Uhvaćeno / Captured CO_2, kg/MWh_e	-	850	-	809	-	1085
Izbjegnuta emisija u zrak / Avoided emission into air, kg/MWh_e(*)	-	574	-	621	-	852
Specifično ulaganje / Specific investment, EUR/kW_e(**)	1020	1855	1370	1860	1270	1790
Trošak pogona i održavanja / Cost of operation and maintenance, EUR/MWh_e	7	13	12	16	3,9	3,9
Trošak izbjegnutog CO_2 / Cost of avoided CO_2, EUR/t CO_2	0	39,3	0	23,1	0	14,7

Napomena / Remark:
(*) Izbjegnuta emisija u zrak = (CO_2 emisija kg/MWh_e iz klasičnog tipa elektrane) – (CO_2 emisija kg/MWhe klasični + HICO2) / Avoided emission into air = (CO_2 emission kg/MWhe from the classic power plant type) – (CO_2 emission kg/MWh_e classic + $CICO_2$)
(**) ulaganja bez troška kapitala i građevinskog zemljišta na zelenoj livadi / investment without capital costs and construction land on green meadows
– procjene specifičnih ulaganja su napravljene prije naglog skoka opreme koncem 2008. godine za 50 % do 70 % / assessments of specific investments have been made before the abrupt leap, at the end of 2008, of 50 % to 70 %
– komprimiranje ugljikovog dioksida / compression of carbon dioxide na / at 100 bar.

Hvatanje i izdvajanje su energetski vrlo intenzivni tehnološki procesi koji imaju za posljedicu značajan porast potrošnje ugljena i prirodnog plina za vlastitu potrošnju. Raspon prirasta vlastite potrošnje procesa se kreće od oko 39 % za današnje izvedbe do očekivanih 6 % za napredne izvedbe u budućnosti iza 2025. Energetska efikasnost proizvodnje električne energije je jedan od preduvjeta za korištenje HITS u energetskom sektoru. Naknadna dogradnja HITS-a na vrlo efikasne kombi blokove ložene prirodnim plinom bi možda mogla

Energy-wise, capture and isolation are very intensive technological processes the consequence of which is significant increase of consumption of coal and natural gas for own consumption. The scope of increment of own process consumption fluctuates from about 39 % for today's performance up to the expected 6 % for advanced performances in the future after 2025. Electricity production energetic efficiency is one of the preconditions for the use of the CITS in the energy sector. Subsequent upgrading of the CITS to very efficient combibiti opravdana opcija, ukoliko cijena prirodnog plina bude dovoljno niska.

Noviji tehnološki postupci, često špekulativne naravi, zasnovani na separatorima, izgaranju kisikom u kombinaciji s naprednim rješenjima za njegovu proizvodnju, kemijskoj petlji i ćelijama goriva, smatraju se obećavajućim za smanjivanje vlastite potrošnje procesa HICO2. Kombiniranje biomasom loženih postrojenja za rasplinjavanje goriva s HITS-om može postati veoma prihvatljivo, čak i za mnogo manja postrojenja od ugljenom loženih postrojenja za rasplinjavanje i to zbog dvostruke koristi od CO_2 u usporedbi prema ugljenu s HITS-om. Takva kombinacija ima negativnu emisiju, jer se ugljik iz biomase temelji na CO_2 koji je uhvaćen iz atmosfere (i može ponovno biti vraćen ili izdvojen).

4 TEHNOLOGIJA TRANSPORTA IZDVOJENOG CO_2

CO_2 može biti transportiran cjevovodima, željezničkim cisternama i brodovima. U praksi, zbog velikog volumena, jedino su transport cjevovodima i brodovima troškovno prihvatljivi. Općenito se smatra da transportni troškovi, bez obzira na rastojanja i količine, trebaju biti manji dio ukupnih troškova HITS-a. Troškovi transporta CO_2po jedinici težine su daleko niži, nego za prirodni plin ili vodik, jer je CO_2 u tekućem ili nadkritičnom stanju 10 do 100 puta veće gustoće. Zbog toga je, po jedinici težine, transport CO_2 troškovno mnogo sličniji transportu nafte nego prirodnog plina ili vodika. Inženjerska studija za termoelektranu Karsto u Norveškoj, na prirodni plin, ukazuje da transport cjevovodom predstavlja 40 % ukupnih ulaganja u HITS. Opisani slučaj je specifičan jer će se cjevovod velikih dimenzija polagati površinski zbog specifičnih geoloških uvjeta.

Transport cjevovodom je nepobitno dokazana tehnologija u dugogodišnjoj praksi i ne predstavlja poseban rizik, ukoliko se odabere odgovarajuća komercijalno provjerena oprema sukladna zakonskoj regulativi. Trenutačno je na globalnoj razini aktivno oko 3 100 km cjevovoda, godišnjeg kapaciteta oko 45 Mt CO_2 na tlaku 120 bar do 140 bar. Nije bilo incidenata velikog rizika po okoliš. Prikladno smješteni HITS projekti mogu značajno smanjiti potrebu za ekstenzivnim transportnim sustavima. Iznuđeni smještaj HITS projekata, poput postojećih lokacija termoelektrana, transportne sustave može povećavati stotinama kilometara, tada je nužno izgraditi magistralnu transportnu mrežu na koju bi bio priključen veći broj termoelektrana i spremnika CO_2 radi smanjenja troškova izgradnje i pogona.

nation blocks fired by natural gas could be a justified option if the natural gas price was low enough.

Recent technological procedure, often of speculative nature, based on separators, oxygen combustion in combination with advanced solutions for their production, the chemical loop and fuel cells, are considered promising for the reduction of own consumption of the CICO2 process. Combining the biomass-fired carburetion plants with the CITS could become very acceptable, even for plants much smaller than the coal-fired carburetion plants and that because of the double benefit of CO_2 in comparison with the coal combined with the CITS. Such a combination has negative emission because the coal from the biomass is based on CO_2 captured from the atmosphere (which can be returned or isolated).

4 THE TECHNOLOGY FOR THE TRANSPORT OF THE ISOLATED CO_2

CO_2 can be transported by pipelines, railway tankers and ships. In practice, because of the extensive volume, only transport by pipelines and ships is acceptable as regards their costs. It is generally considered that transport costs, regardless of the distance and the quantities, have to be lower than the total CITS costs. The costs for the transport of CO_2 per weight unit are by far lower than for natural gas or hydrogen because CO_2 in liquid or supercritical state is of 10 or 100 times greater density. Thus, according to the weight unit, CO_2 transport is cost-wise much more similar to oil transport than to natural gas or hydrogen transport. Engineering study for the Karsto thermal power plant in Norway, fired by natural gas, shows that transport by pipelines makes 40 % of total investments into the CITS. The above case is specific because the large-size pipeline will be laid superficially due to specific geological conditions.

Transport by pipelines is a technology irrefutably proven through years of practice and does not represent a special risk if adequate, commercially tested, equipment, compliant with legal regulations, is chosen. At the moment, at the global level, about 3 100 km pipelines are active, and their annual capacity amounts to about 45 Mt CO_2 at the pressure of 120 bar to 140 bar. There were no incidents of high risk for the environment. Suitably positioned CITS projects could significantly reduce the need for extensive transport systems. The extorted location of CITS projects, such as the existing locations of thermal power plants, can expand the transport systems by hundreds of kilometres; therefore, it is necessary to build a main transport network onto which a significant number of thermal power plants and CO_2 reservoirs would be connected for the purpose of reducing construction and operation costs.

Materijali cjevovoda tijekom pogona mogu biti izloženi koroziji zbog prisustva SO_2 i vode (stvara se sumporna kiselina). Sumpor se pretvara u H_2S u anaerobnom okruženju (npr. CO_2 proces hvatanja u postrojenjima za rasplinjavanje fosilnih goriva), a i izgaranje u čistom kisiku ima za posljedicu stvaranje SO_2. Ograničeno pročišćavanje CO_2 može stvarati dodatne troškove uklanjanja SO_2. H_2S može bez problema biti injektiran zajedno s CO_2, što je provjereno u Kanadi tijekom pogona u referentnom naftnom polju s 43 bušotine, organiziranom od Alberta Research Council i Alberta Energy Utilities Board [8].

Prijevoz izdvojenog CO_2 brodovima, gdje je to moguće, svakako treba razmatrati kao realnu opciju. Transport brodovima je nepobitno isplativa tehnologija za transport velikih količina, preko 1 000 t CO_2. Trenutačno plove brodovi kapaciteta do 1 500 m^3 CO_2. Europska unija priprema projektnu dokumentaciju za brodove kapaciteta 20 000 m^3. Brodski transport može postati veoma značajan, budući da se mnoga potencijalna podzemna spremišta ne nalaze u neposrednoj blizini izvora emisije CO_2. Na primjer, većina budućih potencijalno značajnih spremnika su iscrpljena ležišta nafte na Srednjem Istoku, ili napuštena plinska polja u Rusiji i na Srednjem Istoku. Nasuprot njima, u industrijski razvijenim zemljama se nalaze glavni izvori emisije CO_2. Sve dok se ne razvije međuregionalni transport (npr. Kina – Bliski Istok) iskorištavanje tih spremnika neće biti moguće. Kod naprednog korištenja metana istisnutog iz ležišta ugljena, transport CO_2 se općenito smatra tehnički jednostavnim budući da su specifična nalazišta ugljena rasprostranjenija bliže točkama emisije CO_2.

Tekući CO_2 ima gustoću od 1,0 t/m^3 do 1,5 t/m^3 u usporedbi prema 0,454 t/m^3 za ukapljeni prirodni plin (LNG). Spremnici za CO_2 se izrađuju od jeftinijih materijala jer se transport odvija na temperaturama od – 50 °C u usporedbi prema – 162 °C za LNG. Troškovi transporta brodom su približno jednaki transportu podmorskim cjevovodima na jednakom rastojanju od 500 km, dok je transport kopnenim cjevovodima duplo jeftiniji. Trenutačno bi interkontinentalni transport i troškovi spremanja CO_2 bili po vrlo grubim procjenama u rasponu od 25 USD/t CO_2 do 50 USD/t CO_2 za rastojanje oko 6 000 km. Procjena je temeljena na troškovima transporta LNG [8].

Globalna proizvodnja i brodski transport nafte iznose oko 3,5 Gt/god, globalna proizvodnja i transport ugljena iznose oko 3,8 Gt/god svjetska proizvodnja cementa je oko 1,6 Gt/god dok se oko 2,1 Gt/god žitarica preveze brodskim prostorom. Uz pretpostavku da je emisija CO_2 u svijetu oko 25 Gt/god; jednog dana možda ukupni brod-

During operation, pipeline materials can be exposed to corrosion due to the presence of SO_2 and water (sulphuric acid is generated). Sulphur turns into H_2S in an anaerobic environment (e.g. the CO_2 capture process in fossil fuels carburetion plants), and the combustion in pure oxygen also results in the generation of SO_2. Limited refinement of CO_2 can create additional costs of removal of SO_2. H_2S can easily be injected together with CO_2, which has been verified in Canada during operation in the relevant oil field with 43 boreholes, organized by Alberta Research Council and Alberta Energy Utilities Board [8].

The transport of the isolated CO_2 by ships, where possible, should absolutely be considered as a realistic option. Transport by ships is irrefutably a cost-effective technology for the transport of quantities over 1 000 t CO_2. At the moment, ships with capacities of 1 500 m^3 CO_2 are sailing. The European Union is preparing project documentation for ships with capacities of 20 000 m^3. Ship transport could become very important because many potential underground reservoirs are not located in the direct vicinity of the CO_2 emission sources. For example, most of the reservoirs which could become important in the future are the exhausted oil deposits in the Middle East or the abandoned gas fields in Russia and the Middle East. As opposed to these, the main sources of CO_2 emissions are located in the industrially developed countries. Until interregional transport is developed (e.g. China - the Middle East) the exploitation of those reservoirs will not be possible. In advanced use of methane extracted from coal deposits, CO_2 transport is generally considered to be technically simple because the specific coal sites are more densely spread closer to the points of CO_2 emission.

Liquid CO_2 has a density of 1,0 t/m^3 up to 1,5 t/m^3 in comparison with 0,454 t/m^3 for liquefied natural gas (LNG). CO_2 reservoirs are made of cheap materials because the transport takes place at temperatures of – 50 °C in comparison with – 162 °C for the LNG. Costs of transport by ship are about the same as those of transport by underwater pipelines taking the same distance of 500 km, while transport by continental pipelines is half as cheap. At the moment, intercontinental transport and costs of CO_2 storage would, as a very rough estimate, be in the scope from 25 USD/t CO_2 to 50 USD/t CO_2 for the distance of 6 000 km. The estimate is based on transportation costs for the LNG [8].

Global production and oil transport by ship amount to about 3,5 Gt/year of global production and transport of coal amount to about 3,8 Gt/year, global cement production is about 1,6 Gt/year while about 2,1 Gt/year of cereals are transported by ship. Under the assumption that the CO_2 emission in the world is about 25 Gt/year, one day, the total ship transport of CO_2 may come to the same level as the transport of all specified goods taken together! Because of ski prijevoz CO_2 može biti istog reda veličine kao i transport svih specificiranih roba zajedno! Zbog toga izazovi koji stoje pred razvojem sustava za transport CO_2 nikako ne smiju biti podcijenjeni. Neki stručni krugovi smatraju organiziranje globalnog transporta upitnim u bliskoj budućnosti te polažu nade u razvoj spekulativne tehnologije uklanjanja ugljikovog dioksida iz zraka!

that, the challenges which are set before the CO_2 transport system should not be underestimated no matter what. Some professional circles believe that the organization of the global transport in the near future is questionable and they have expectations as regards the development of speculative technology for the removal of carbon dioxide from the air!

5 TEHNOLOGIJA SPREMANJA CO_2

Generalno, jedina realna opcija u idućem kratkoročnom i srednjoročnom vremenskom periodu planiranja je podzemno skladištenje CO_2 u dubokim ležištima nafte, plina, ugljena i naslagama propusnih stijena koja sadrže vodu visokog saliniteta (u nastavku slani vodonosnik).

U drugi plan se stavlja mogućnost spremanje u oceane i nadzemno skladištenje i to zbog rizika po okoliš i problema koji mogu pratiti spremanje i nadzor spremljenog CO_2.

Teoretski potencijal i kapacitet spremanja CO_2 u duboke slane vodonosnike se procjenjuje na 1 000 Gt do 10 000 Gt, što omogućava spremanje decenijima i stotinama godina. Naslage slanih vodonosnika, kao potencijalnih spremnika, su daleko ravnomjernije raspoređene od ležišta nafte i prirodnog plina. Trenutačno vrlo uspješno radi odlaganje CO_2 u slani vodonosnik Sleipner (Norveška) [9] kapaciteta 1 000 kt/god. Usporedbe radi, proizvodna postrojenja Hrvatske elektroprivrede d.d. imaju godišnju emisiju oko 6 000 kt CO_2.

Duboka nalazišta plina i nafte mogu pohranjivati decenijima emisiju CO_2 uz prihvatljiv stupanj rizika. Injektiranje CO_2 radi unaprjeđenja iskorištenja ležišta fosilnih goriva može postati, rana i ključna, povoljna prilika za spremanje, i to posebno onda, kada se mogu ostvariti prihodi koji pokrivaju sve ili dio troškova HITS. Realizirano je nekoliko projekata od kojih je najveći lociran u Weyburnu (USA/Kanada) kapaciteta 2 000 kt/god s ciljem povećanja iscrpka nafte i Snøhvit (Norveška) 700 kt/god u slani vodonosnik. Projekti su pokazali pogonsku sposobnost spremanja CO_2 u podzemna skladišta. Svi navedeni projekti su namijenjeni za povećanje iscrpka nafte injektiranjem CO_2 ili kiselih plinova u bušotine. Potencijal ovakvih projekata nije do sada dovoljno distribuiran.

Trenutačno se istraživanje i razvoj tehnološkog postupka skladištenja fokusira na sljedeće opcije:

— povećanje iscrpka nafte utiskivanjem CO_2 u ležište, (u nastavku EOR)

5 CO_2 STORAGE TECHNOLOGY

Generally, the only real option in the following short-term and middle-term planning period is underground storage of the CO_2 in deep oil, gas and coal deposits and layers of porous rocks which contain high-salinity water (hereinafter: saline aquifer).

The position of second importance is given to the possibility of storage in oceans and surface storage and that without risk for the environment and the problems which could accompany the storage and supervision of the stored CO_2.

Theoretically, the potential and capacity of CO_2 storage in deep saline aquifers is estimated at 1 000 Gt up to 10 000 Gt which enables storage for decades and hundreds of years. Saline aquifers layers, as potential reservoirs, are far more equally spread than oil and natural gas deposits. At the moment, the storage of CO_2 into the Sleipner saline aquifer (Norway) [9] with the capacity of 1 000 kt/year is operating very successfully. For the purpose of comparison, the plants of Hrvatska elektroprivreda d.d. have annual emissions of about 6 000 kt CO_2.

Deep gas and oil sites can store CO_2 emissions for decades with an acceptable risk level. CO_2 injections for the purpose of improvement of employment of fossil fuel layers can become an early favourable chance for storage with key importance, especially when income can be realized which covers all or a part of the CITS costs. Several projects have been realized – the greatest of these is located in Weyburn (USA/Canada) and has a capacity of 2 000 kt/year – its purpose is enhanced oil recovery; and Snøhvit (Norway) has a capacity of 700 kt/year – into the saline aquifer. The projects have shown the plant's capability of storing CO_2 in underground reservoirs. All the above projects are intended for enhanced oil recovery by injection of CO_2or acid gases into the boreholes. The potential of these projects has not been distributed enough so far.

At the moment, research and development of the technological process of storage focuses on the following options:

— enhanced oil recovery by CO_2 injection into the

— povećanje iscrpka prirodnog plina utiskivanjem CO_2 u ležište, (u nastavku EGR),
— povećanje iscrpka metana utiskivanjem CO_2 u ležišta ugljena, (u nastavku ECBM),
— spremanje u iscrpljena ležišta nafte ili prirodnog plina,
— spremanje u duboke slane vodonosnike (u nastavku SA),
— ostale opcije skladištenja.

U većem broju objavljenih studija se navodi da će troškovi skladištenja biti sekundarne važnosti u usporedbi s troškovima hvatanja i transporta. Tvrdnja je jedino točna ukoliko je trošak kompresije uključen u troškove hvatanja i transporta. Troškove je vrlo teško uprosječiti budući da osciliraju ovisno od slučaja do slučaja 5 (čak i 10) puta. Radi jednostavnije analize je pretpostavljena vrijednost tlaka skladišta od 100 bar. Tlak utiskivanja i rastojanje na koje se transportira određuju polazni tlak CO_2. Tlak utiskivanja je ovisan o dubini injektiranja i o tlačnom profilu u podzemlju. Minimalna dubina skladištenja je oko 800 m (na toj dubini je CO_2 u superkritičnom stanju). U superkritičnom stanju ne postoji vidljivi prijelaz iz plinovitog u tekuće stanje pri porastu tlaka. Gustoća CO_2 pri 100 °C i 200 bar je 0,5 t/m^3 a pri 500 bar 0,8 t/m^3. Lokalni tlak i temperatura određuju gustoću CO_2 i ona se obično kreće u rasponu od 0,61 t/m^3 do 0,72 t/m^3.

Većina potencijalnih spremnika je locirana na dubinama 2 km do 4 km ispod površine. Za spremnike na dubinama od 800 km, može biti dovoljan tlak utiskivanja od 100 bar. Međutim spremanja u iscrpljena ležišta plinskih polja će zahtijevati površinski tlak pred utiskivanjem od 200 bar do 300 bar, tablica 4. Sastavni dio tehnološkog postupka je i recirkuliranje CO_2, na čega se troši veoma značajna energija. Na primjer, u praksi kod povećanja iscrpka nafte utiskivanjem CO_2 u ležište, u stalnoj recirkulaciji se nalazi od 16 % do 40 % mase CO_2 koja se utiskuje (20 % do 67 % se obično u konačnici trajno zadrži u sloju!).

Kod povećanja iscrpka prirodnog plina utiskivanjem CO_2 u ležište, količina zadržanog i uskladištenog CO_2 u sloju, kojom se postiže željeni učinak, iznosi skromnih 14 %! Recirkulirana količina CO_2, kod opcije povećanja iscrpka metana utiskivanjem u ležišta ugljena, može biti vrlo velika ukoliko CO_2 kroz pukotine stijena obilazi ležište ugljena/metana ili ako samo ležište već sadrži veću količinu prirodnog CO_2. Prosječno se, u opciji utiskivanja u ležište ugljen/metan obično zadržava oko 20 %.

deposit, (hereinafter EOR)
— enhanced natural gas recovery by CO_2 injection into the deposit, (hereinafter EGR)
— enhanced coal bed methane extraction by injection of CO_2 into coal beds, (hereinafter ECBM)
— storage in depleted oil or natural gas deposits,
— storage in deep saline aquifers (hereinafter: SA),
— other storage options.

A large number of published studies state that storage costs will be of secondary importance in comparison with capture and transportation costs. The claim is accurate only if the compression cost is included in capture and transportation costs. It is very difficult to determine the average of the costs because they oscillate, depending on the case, by 5 (even up to 10) times. For the purpose of a simpler analysis, the value of storage pressure is assumed to be 100 bar. The injection pressure and the distance of the transportation are the determinants of the initial CO_2 pressure. The injection pressure depends on the injection depth and the underground pressure profile. The minimum storage depth is about 800 m (at that depth, CO_2 is in supercritical state). At increase of pressure in supercritical state there is no evident transition from gaseous to liquid state. CO_2 density at 100 °C and 200 bar is 0,5 t/m^3 and at 500 bar it is 500 bar 0,8 t/m^3. Local pressure and temperature determine CO_2 density and it usually fluctuates in the scope between 0,61 t/m^3 up to 0,72 t/m^3.

Most potential reservoirs are located at the depths of 2 km to 4 km beneath the surface. For the reservoirs at the depths of 800 km, injection pressure of 100 bar could suffice. However, storage in depleted gas fields will require a surface pressure prior to injection of 200 bar up to 300 bar, Table 4. An integral part of the technological process is also the recycling of CO_2 which consumes a significant amount of energy. For example, in practice, at enhanced oil recovery by injection of CO_2 into the deposit, there is about 16 % up to 40 % of CO_2 mass which is in constant recirculation and which is injected (20 % up to 67 % usually ends up in the layer permanently!).

At enhanced natural gas recovery by injection of CO_2 into the deposit, the amount of CO_2 retained and stored in the layer which enables the achievement of the desired effect, amount to a mere 14 %! The quantity of CO_2 in recirculation, at the enhanced coal bed methane extraction by injection into coal beds, may be very high if the CO_2 roams the coal/methane bed through rock fractures or if the bed itself already contains a large quantity of natural CO_2. At the bed injection option, coal/methane usually lingers at about 20 %.

Tablica 4 – Potrebna energija tlačenja CO_2 za injektiranje ovisno o vrsti spremnika i dubini [9]
Table 4 - CO_2 pressing energy necessary for the injection depending on the type of reservoir and depth [9]

	Tlak od 100 bar na 800 m dubine / Pressure of 100 bar at the depth of 800 m, $GJ_e/t\ CO_2$	Tlak od 200 bar na 1 600 m dubine / Pressure of 200 bar at the depth of 1 600 m, $GJ_e/t\ CO_2$
Povećanje iscrpka nafte utiskivanjem CO_2 / Enhanced oil recovery by CO_2 injection	0,34	0,50
Povećanje iscrpka prirodnog plina utiskivanjem CO_2 / Enhanced natural gas recovery by CO_2 injection	0,25	0,40
Povećanje iscrpka metana utiskivanjem CO_2 / Enhanced coal bed methane extraction by injection of CO_2	0,25	0,40
Spremanje CO_2 u duboke vodonosnike / Storage of CO_2 into deep aquifers	0,22	0,38

5.1 Tehnološki postupci EOR i EGR

Povećanje iscrpka nafte utiskivanjem CO_2 u ležišta donosi najveće prihode u usporedbi s ostalim opcijama. U nekim posebnim slučajevima se spremanjem može jedno vrijeme ostvariti i čista dobit (diktirano potražnjom i cijenom barela nafte). Presudne su geološke formacije i lokacija ležišta u odnosu na izvor CO_2.

U pogonu je 2004. godine bilo 105 skladišta tipa EOR, od kojih se 85 nalazi u SAD i 8 u Kanadi. Veći broj projekata je u različitom stupnju razvoja. Primarni i sekundarni načini iskorištavanja naftnih ležišta općenito imaju za posljedicu iscrpak između 40 % i 50 %. To ovisi od: kompleksnosti i uvjeta u ležištu, strategije iskorištavanja ležišta i ekonomskih kriterija. Dobivanje nafte tercijarnim metodama ili metodama povećanja iscrpka (EOR) ključni je proces nadomještanja ili povećanja rezervi koje se mogu koristiti na ekonomičan način, i to bez primjene konvencionalnih metoda. Utiskivanje raznih plinova se danas smatra drugom (prva je voda) po djelotvornosti metodom povećanja iscrpka nafte. Utiskivanje vode ili plinova u iscrpljena naftna polja povećava tlak u ležištu koji omogućava istiskivanje nafte iz šupljina stijena i strujanje prema proizvodnim bušotinama.

U SAD se tijekom 2003. godine proizvodilo oko 200 000 bbl nafte po danu utiskivanjem CO_2 u naftna ležišta. Ovaj postupak je zastupljen s udjelom od oko 31 % u ukupnoj proizvodnji nafte tercijarnim mjerama povećanja iscrpka. Preostalih 69 % čini utiskivanje dušika, dimnih plinova, ugljikovodika, vodene pare i polimera. Količine CO_2 utisnute radi povećanja iscrpka nafte iznose oko 32 000 kt/god CO_2 iz prirodnih izvora i oko 11 000 kt iz industrijskih procesa. Izvan SAD postoji nekoliko projekata u pogonu. EOR utiskivanje CO_2 radi povećanja iscrpka nafte se primjenjuje više od tri desetljeća i smatra se provjerenom tehnologijom. Međutim, ova tehnologija je razvijena

5.1 EOR and EGR technological procedures

Enhanced oil recovery by injection of CO_2 into the deposits yields the highest income in comparison with the other options. In certain special cases, the storage may, for a certain time, yield pure profit (dictated by demand and oil barrel price) as well. Geological formations and deposit locations as regards the CO_2 source are decisive.

In 2004, 105 storages of EOR type were in operation; 85 of these were located in the USA and Canada. A significant number of projects is in different developmental stages. Primary and secondary methods of oil deposit exploitation generally result in the extraction of between 40 % and 50 %. That depends on: deposit complexity and state, deposit exploitation strategies and economic criteria. Obtainment of oil by tertiary methods or enhanced oil recovery methods (EOR) is the key process for the substitution or increase of reserves which may be used in an economical manner and that without the application of conventional methods. Today, the injection of different gases is considered to be the second most effective method of enhanced oil recovery (the first being the injection of water). The injection of water or gases into depleted oil fields increases the deposit pressure which enables the oil to be extracted from the rocks' cavities and the circulation towards production boreholes.

During 2003, in the USA, about 200 000 bbl of oil were produced daily by injection of CO_2 into oil deposits. This procedure participates with about 31 % in the total oil production by virtue of tertiary enhanced recovery methods. The remaining 69 % includes the injection of nitrogen, flue gases, hydrocarbon, water vapour and polymers. Quantities of CO_2 injected for the purpose of enhanced oil recovery amount to about 32 000 kt/year CO_2 from natural sources and to about 11 000 kt from industrial processes. There are several operating projects outside the USA. EOR CO_2 injection for the purpose of enhanced oil recovery has been implemented for s ciljem povećanja iscrpka nafte, a ne za trajno spremanje CO_2. Povećanje iscrpka nafte tercijarnim mjerama u prosjeku obično povećava ukupno iskorištenje naftnih polja do 50 %. EOR se ne može obično primijeniti na sva naftna polja. Dubina ležišta nafte obično mora biti veća od 600 m. Sirova nafta treba biti gustoće najviše 910 kg/m^3, što čini ovu metodu nepodobnom za teške nafte, uljni pijesak ili ležišta s plinskom kapom. Utiskivanje CO_2 je ograničeno na naftna polja kod kojih je završena proizvodnja primarnim mjerama (tlak ležišta) i sekundarnim mjerama (pumpanje i utiskivanje vode). U slučaju velikih plinskih kapa efikasnost utiskivanja CO_2 je ograničena. Značajan dio utisnutog CO_2 se vraća s naftom i vodom na površinu; tada se CO_2 mora izdvojiti i ponovno utiskivati. Po zatvaranju naftnih polja angažirani CO_2 je trajno spremljen. Do temperatura ležišta od 120 °C, CO_2 se miješa s naftom, dok na višim temperaturama CO_2 nadomješta naftu. Povoljnije je miješanje CO_2 s naftom jer rezultira relativno većim iscrpkom. Miješanje CO_2 i nafte omogućava da se na tonu nafte utisne 2,4 t CO_2 do 3 t CO_2. Procjene potencijala spremanja u bušotine naftnih polja osciliraju i ovise o kriterijima selekcije (troškovi, geološka struktura, koncentracija polja). Nove utisne bušotine za EOR predstavljaju glavni dio ulaganja.

Za EOR treba postojati potencijal od minimalno 5 milijuna barela nafte i više od 10 bušotina. Tada bi ukupni pr fte oko 110 USD/t (15 USD/bbl), uz pretpostavljenu količinu utiskivanja od 2,5 t CO_2 po toni sirove nafte, dobit je oko 25 USD/t CO_2 za gratis količinu CO_2. Pretpostavljena dobit je proračunata za izvrsnu specifičnu utisnutu količinu; što kod većine ležišta nafte nije moguće postići, tako da je i dobit znatno manja.

U većini polja je nužno bušiti nove utisne bušotine, budući da su stare eksploatacijski nepouzdane; zapažena su izbijanja CO_2 kroz zabrtvljene bušotine. Tehno-ekonomske analize opravdanosti mogu, zbog velikog broja nepoznanica podcijeniti potencijal tehnologije EOR; što je slučaj s utiskivanjem u polja Sjevernog mora kod kojih je iscrpak udvostručen.

EGR je teoretska metoda podizanja tlaka u iscrpljenim (oko 85 %) plinskim ležištima. Podobna iscrpljena ležišta metana imaju tlak od 20 bar do 50 bar. Bez obzira na stanje u kojem se nalazi, CO_2 (plinovito, tekuće ili superkritično) je značajno gušći od CH_4 pri svim relevantnim tlakovima i temperaturama i ima tendenciju strujanja na niže pri utiskivanju u bušotinu, što ima za posljedicu istiskivanje prirodnog metana i podizanje tlaka u ležištu. Utiskivanje CO_2 do 2007. godine nije korišteno u komercijalne svrhe. Postoje dvojbe oko opravdanosti primjene ove teoretske metode. Sve ovisi o vremenu potrebom da CO_2

more than three decades and is considered tested technology. However, this technology has been developed with the aim to increase oil recovery and not for permanent storage of CO_2. Enhanced oil recovery by tertiary measures usually increases the total exploitation of oil fields by up to 50 % in the average. The EOR usually cannot be applied to all oil fields. Oil deposit depth usually has to be over 600 m. Crude oil density has to be at the most, and this makes this method ineligible for heavy oils, oil sands or gas-cap deposits. CO_2 injection is limited to oil fields in which the production by primary methods (deposit pressure) and secondary methods (pumping and water injection) is completed. In case of large gas caps, the efficiency of CO_2 injection is limited. A significant share of the injected CO_2 comes back with oil and water onto the surface; CO_2 must then be separated and re-injected. After the sealing of the oil fields, the employed CO_2 is stored permanently. Up to the deposit temperatures of 120 °C, CO_2 is mixed with oil, while at higher temperatures, CO_2 substitutes oil. Mixing with CO_2 is more favourable because it yields relatively higher extraction ratios. Mixing CO_2 and oil provides for the injection of 2,4 t CO_2 up to 3 t CO_2 per ton of oil. Estimates of the potential of the storage in oil field boreholes vary and depend on the selection criteria (costs, geological structure, field concentration). New injection boreholes for the EOR constitute the major part of the investment.

The EOR requires the potential of at least 5 million oil barrels and more than 10 boreholes. Total production costs would then amount to (without the CO_2 cost) about 50 USD/t (7 USD/bbl). If at the top of the borehole the oil price is about 110 USD/t (15 USD/bbl) with the presumed amount of injection of 2,5 t CO_2 per ton of crude oil, the profit is about 25 USD/t CO_2 for a gratis amount of CO_2. The predicted profit is calculated for an excellent specific injected quantity and this cannot be achieved in most oil deposits and therefore the profit is lower as well.

In most of the fields, new injection boreholes need to be drilled because the old ones are unreliable for exploitation; CO_2 bursts through sealed boreholes have been recorded. Technological-economical justifiability analyses could, because of the large number of unknown terms, underestimate the potential of the EOR technology which is the case with the injections into the Northern Sea fields which yield double extraction ratios.

EGR is the theoretical method of pressure increase in depleted (about 85 %) gas deposits. Eligible depleted methane beds have pressures of 20 bar up to 50 bar. Regardless of its state (gaseous, liquid or supercritical), CO_2 is significantly denser than CH_4 at all relevant pressures and temperatures and has the tendency of downward flow at injection into the borehole, the consequence of which is the extracdopre do plinskog ležišta. Procjenjuje se da kapacitet spremanja CO_2 u plinska ležišta ima veći potencijal od mogućnosti spremanja u ležišta nafte. Tehno-ekonomskim analizama opravdanosti većeg broja projekata su utvrđeni značajno manji prihodi (npr. oko 1,8 GJ prirodnog plina se dobije utiskivanjem jedne tone CO_2) nego kod utiskivanje u ležišta nafte.

5.2 Spremanje u iscrpljena ležišta nafte ili prirodnog plina

Operacija spremanja je vrlo jednostavna budući da jedino treba izgraditi utisne bušotine (ovisno o geologiji polja i brzini utiskivanja). Veći dio postojeće infrastrukture se može iskoristiti, što znatno smanjuje ulaganja. U budućnosti će potencijal spremanja rasti jer će biti sve veći broj iscrpljenih ležišta nafte i plina i to naročito na Bliskom istoku i u zemljama bivšeg SSSR-a. Korištenje njihovog potencijala će podrazumijevati brodski transport CO_2 do tih regija; što u suštini smanjuje njihov ekonomski potencijal. Ukupni iskoristivi kapacitet spremanja u iscrpljena ležišta prirodnog plina se procjenjuju na 1 000 Gt CO_2 i odgovara svjetskoj emisiji od 50-ak godina.

Ovo je vrlo gruba teoretska procjena kapaciteta iscrpljenih ležišta, stvarni potencijal može biti bitno reduciran prirodnim zavodnjavanjem (potapanjem) i nemogućnošću postizanja izvornog tlaka ležišta.

Važno je napomenuti da je odlaganje u iscrpljena i napuštena ležišta nafte i prirodnog plina (uključujući i opcije povećanja iscrpka aktivnih ležišta) osjetno manji rizik nego spremanje u duboke slane vodonosnike, budući da je geologija vodonosnika često velika nepoznanica.

5.3 Odplinjavanje ležišta ugljena od metana

Povećanje iscrpka metana (ugljeni plin) iz ležišta ugljena je spekulativna metoda. Kod konvencionalnog iskorištenja metana iz ležišta ugljena se može postići 40 % do 50 % iscrpka u neposrednoj blizini bušotine, dok se u slučaju utiskivanja CO_2 iscrpak teoretski može povećati na 90 % do 100 %. ECBM je ograničen na ležišta ugljena koja nije moguće eksploatirati ili nisu tehno-ekonomski isplativa, što je glavni izvor neizvjesnosti koji ovisi o razvoju rudarske tehnologije i energetskih potreba. ECBM se može primijeniti u ležištima ugljena dovoljne propusnosti. Porastom tlaka, adsorpcija CO_2 raste od 2 mola/molu metana na 700 m na 5 mola/molu na 1 500 m. Rezerve ugljena ne smiju biti na dubinama većim od 2 000 m jer porast temperature ograničava sadržaj metana u ugljenu, a porast tlaka na većim dubinama

tion of natural methane and increase of pressure in the deposit. Until 2007, injection of CO_2 has not been used for commercial purposes. It is not certain whether the application of this method is justified. It all depends on the time necessary for CO_2 to reach the gas deposit. The capacity of CO_2 storage in gas deposits is estimated to be of larger potential than the possibility of storage into oil deposits. Technological-economical justifiability analyses of many projects determined much lesser income (e.g. about 1,8 GJ of natural gas is obtained by injection of one ton of CO_2) than at injection into oil deposits.

5.2 Storage in depleted oil or natural gas deposits

The storage activity is quite simple because only injection boreholes need to be constructed (depending on the field geology and the injection speed). Most of the existing infrastructure can be used and this significantly reduces the investments. The storage capacity will grow in the future because the number of depleted oil and gas deposits will grow, particularly in the Middle East and the former USSR countries. The use of the potential thereof will require ship transport of CO_2 to those regions; this basically reduces their economic potential. Total useful capacity of storage into depleted natural gas deposits is estimated at 1 000 Gt CO_2 and this equals some 50 years of world emission.

This is a very rough theoretical estimate of the depleted deposits' capacity; actual capacity may be significantly reduced by natural inundation (flooding) and by the inability to achieve the original deposit pressure.

It is important to mention that disposal into depleted and abandoned oil and natural gas deposits (including the options of increase of active deposit extraction ratios) bears significantly less risk than storage into deep saline aquifers, as the geology of the aquifers is often a great unknown.

5.3 Coal seams methane degassing

Enhanced methane (coal gas) extraction from coal seams is a speculative method. At conventional exploitation of methane from coal seams, in the direct vicinity of the borehole, 40 % up to 50 % can be obtained, while in the case of injection of CO_2, the extraction ratio can theoretically rise to 90 % up to 100 %. ECBM is limited to coal seams which cannot be exploited or which are not technologically-economically cost-effective. This is the main source of uncertainty and it depends on the development of mine technology and energy requirements. ECBM can be applied in coal seams of sufficient permeability. By increase of pressure, the CO_2 adsorption increases from 2 mol/ 1 mol of methane at 700 m to 5 mol/1 mol methane at 1 500 m. Coal reserves must not be smanjuje propusnost ležišta. Sadržaj metana u dubokim ležištima može varirati od 5 m^3/t do 25 m^3/t ugljena ovisno od debljine sloja (i ostalim značajkama), tako da ECBM potencijal po bušotini i troškovima spremanja CO_2 varira s faktorom pet i više. To znači da su najatraktivnije opcije s gledišta iscrpka metana - plitke rezerve ugljena debelog sloja, ali one često ne ispunjavaju temeljne kriterije eksploatacije.

Selekcija ležišta ugljena za ECBM se mora temeljiti na kriterijima kao što su:

— homogena rezerva,
— poprečna i vertikalna izoliranost od okolnih slojeva,
— minimalna ispresijecanost rasjedima i naborima,
— propusnost minimalno od, $1x10^{-15}$ m^2 do $5x10^{-15}$ m^2, većina ugljenih ležišta su mnogo manje propusnosti.

Kriterije prema iskustvenim procjenama zadovoljava manji broj potencijalnih ležišta. Visoki sadržaj metana, stratigrafički koncentriranog ležišta je u prednosti nad višeslojnim ležištem. Mogućnost iskorištenja ili eksport metana cjevovodom kao i raspoloživost CO_2 (lokalne termoelektrane, industrija ili magistralni cjevovodi za CO_2) pozitivno utječu na selekciju ležišta. Svjetski potencijal spremanja u duboka neeksploatabilna ležišta ugljena se procjenjuje na 150 Gt CO_2. Analize pokazuju da samo 5 Gt CO_2 do 15 Gt CO_2 ECBM projekata pokazuje moguću profitabilnost, dok oko 50 Gt kapaciteta može biti korišteno s umjerenim troškovima spremanja, ispod 50 USD/t CO_2, u koje nisu uključeni troškovi hvatanja i transport (IEA GHG Programme, 1998). Uz pretpostavku da 2 mola CO_2 zamjenjuje jedan mol metana, utisnutih 10 Gt CO_2 odgovara energiji od 90 EJ (E = eksa = 1018=trilijun) sadržanoj u prirodnom plinu potrošenom tijekom jedne godine u svijetu! Masovnije iskorištenje ECBM tehnologije se zbog toga trenutačno smatra fikcijom u realnom elektroenergetskom sektoru.

Ugljen je sklon bubrenju u kontaktu s CO_2 što ima za posljedicu redukciju propusnosti. Niska propusnost, u nekim slučajevima, može biti nadjačana pucanjem formacije sloja ugljena. Trošak izgradnje bušotina za utiskivanje eksponencijalno raste s dubinom ležišta ugljena; koso bušenje je 70 % skuplje od vertikalnog bušenja. Velika gustoća utisnih bušotina je presudno potrebna za ECBR. Troškovi utisnih bušotina predstavljaju ¾ ukupnih troškova. Vrlo teško je generalno odrediti ukupne troškove za velike razmjere primjene, budući da osjetno variraju od slučaja do slučaja. Veliki broj bušotina dodatno smanjuje upotrebljivost zemljišta. Kod plitkih nalazišta ugljena pojava i problem dreniranja vode

at depths exceeding 2 000 m because the increase of temperature limits the content of methane in the coal, and the increase of pressure at greater depths reduces deposit permeability. Methane content in deep deposits may vary from 5 m^3/t up to 25 m^3/t of coal, depending on layer thickness (and other properties) and therefore the ECBM potential per borehole and CO_2 storage costs vary with a factor of 5 or more. This means that the most attractive options, from the aspect of the methane extract, are shallow thick-layer coal reserves but these often do not meet the basic exploitation criteria.

Selection of coal seams for the ECBM must be based on criteria such as:

— homogenous reserve,
— transverse and vertical isolation from the surrounding layers,
— minimal intersection by faults and folds,
— permeability of at least $1x10^{-15}$ m^2 up to $5x10^{-15}$ m^2, most coal deposits are of significantly lesser permeability.

According to experiential estimates, only a small number of potential deposits meets the criteria. High methane content of a stratigraphically concentrated deposit is preferable to the multi-layer deposit. The possibility of exploitation or export of methane by pipelines as well as the availability of CO_2 (local thermal power plants, industry or main CO_2 pipelines) positively impact the deposit selection. The global potential of storage into deep non-exploitable coal seams is estimated at 150 Gt CO_2. Analyses show that only 5 Gt CO_2up to 15 Gt CO_2 of ECBM projects show potential profitability, while about 50 Gt of the capacity can be used with moderate storage costs lower than 50 USD/t CO_2 and exclusive of capture and transportation costs (IEA GHG Programme, 1998). Under the presumption that 2 mol of CO_2 substitute one mol of methane, injected 10 Gt CO_2 equal the energy of 90 EJ contained in natural gas used in a year throughout the world! Mass exploitation of the ECBM technology is therefore currently not viewed as fictive in the real electric power sector.

Coal tends to expand in contact with CO_2 which results in reduced permeability. Low permeability, in some cases, can be overcome by a burst of the coal layer formation. The cost of construction of injection boreholes increases exponentially with the depth of the coal deposit; diagonal drilling is by 70 % more expensive than vertical drilling. High density of injection boreholes is decisively necessary for the ECBR. Costs of injection borehole represent 3/4 of total costs. It is very hard to determine generally the total costs for wide application scopes because they vary significantly from case to case. A large number of boreholes further reduces land exploitability. With shallow coal deposits, the occurrence iz slojeva ugljena može prouzročiti tonjenje tla, a kod dubokih ležišta problem zbrinjavanja slane vode može biti naglašen. Današnji pilot projekti ECBM se nalaze u SAD i Kanadi, a treći je u razradi, u Poljskoj. Dosadašnji rezultati nisu dovoljno uvjerljivi i smatraju se nedovoljnim za generalne zaključke vezane za dalji razvoj komercijalizacije ECBM. Studija za projekt ECBM u Nizozemskoj pretpostavlja specifičnu cijenu transporta i spremanja u rasponu od 50 USD/t CO_2 do 75 USD/t CO_2 bez troškova hvatanja i izdvajanja i to pri cijeni plina od 3,5 USD/GJ.

Zaključiti se može da je tehnologija ECBM u ranom stupnju razvoja, tako da je njena perspektiva još uvijek neizvjesna. Po realizaciji nekoliko većih razvojnih projekata moći će se nakon njihove višegodišnje eksploatacije dati meritorna ocjena o njihovoj sigurnosti i okolišnoj prihvatljivosti. U većini slučajeva će dobit biti limitirana gubitcima zbog nepredvidivih dodatnih troškova.

5.4 Spremanje u duboki slani vodonosnik

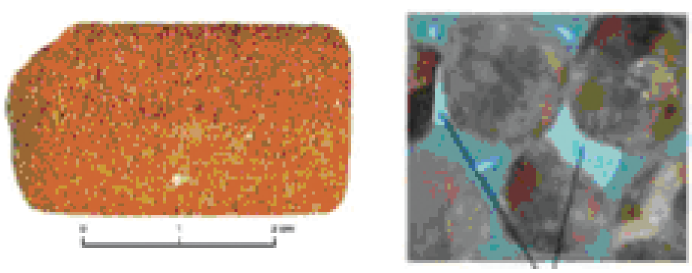
Slani vodonosnik je sloj sedimentnih stijena, zasićenih vodom, u koje se može ukoliko su zadovoljavajuće poroznosti utiskivati fluid. Porozni vodonosnici čvrste spužvaste strukture su prikazani na slici 4. Karbonatne stijene su obično vodonosnici zadovoljavajuće poroznosti.

and the problem of draining water from coal layers can cause soil sinking, and in deeper layers, the problem of disposal of saline water could be pronounced. Today's ECBM pilot projects are located in the USA and Canada and the third is being elaborated in Poland. Results so far are not convincing enough and are considered insufficient to make general conclusions for the further development of ECBM commercialization. The study for the ECBM project in the Netherlands presumes the specific transport and storage price in the range between 50 USD/t CO_2 up to 50 USD/t CO_2 exclusive of capture and isolation costs and that being at the price of gas of 3,5 USD/GJ.

The conclusion can be drawn that the ECBM technology is at an early phase of development, so that its perspective is still uncertain. After the implementation of a few larger projects and several years of exploitation, a merit-based assessment of their safety and environmental acceptability will be made. In most cases, the profit will be limited by losses due to unpredicted additional costs.

5.4 Storage in deep saline aquifers

A saline aquifer is a layer of water-protected sedimentary rocks into which fluid can be injected if they are of adequate porosity. Porous aquifers of solid spongy structure are shown in Figure 4. Carbonate rocks are usually aquifers of adequate porosity.



Slika 4 — Pješčenjak duljine 2 cm (lijevo) i karbonatna stijena (desno) [10]
Figure 4 — 2-cm long sandstone (left) and carbonate rock (right) [10]

Voda zadržana milijunima godine u porama i pukotinama stijena sadrži visoku koncentraciju otopina, obično je to slana voda neprikladna za piće. Kristalno i metamorfno kamenje, poput granita, nema potrebnu poroznost za skladištenje CO_2, ali ukoliko se nalazi iznad sloja pješčenjaka, funkcionira kao prirodno brtvilo. Otvoreni i uski vodonosnici nemaju prirodnih barijera za strujanje vode, tako da se odvija spora prirodna cirkulacija i nažalost nisu podobni za skladištenje CO_2.

U Norveškoj se na plinskom ležištu Sleipner, separirani CO_2 skladišti u slani vodonosnik ispod

Water which has been kept for millions of years in pores and crevices contains a high concentration of solvents and this is usually saline water unsuitable for drinking. Crystal and metamorphic stones, such as granite, do not have the necessary porosity for the storage of CO_2, but if located above the sandstone layer, they operate as natural sealants. Open and narrow aquifers do not contain natural barriers for water flow, so that slow and natural circulation takes place and thus these are unfortunately not adequate for storage of CO_2.

In Norway, in the Sleipner gas deposit, the separated CO_2 is stored in the saline aquifer under the gas plinskog ležišta. Skladišti se oko 1 Mt CO_2 godišnje od 1996. godine. Skladištenje je tehnički potpuno opravdano. Uočena su očekivana kretanja ugljikovog dioksida prema površini, a propuštanja nisu uočena. Specifična investicija (komprimiranje i utiskivanje) je iznosila 80 USD/t CO_2 . Nije moguće niti nakon niza ispitivanja točno procijeniti potencijal skladištenja (potencijal preostalih slobodnih pora). Konzervativne procjene su se kretale oko 2 % kapaciteta jedinice volumena, ali su kasnija istraživanja pokazala da bi se moglo uz niže troškove iskoristiti između 13 % i 68 % jedinice volumena pravilnim odabirom rasporeda i broja bušotina. Novi Norveški projekt Snøhvit (komprimiranje, transporta i utiskivanje) je procijenjen na 275 USD/t CO_2, najveći udio ulaganja se odnosi na komprimiranje i transport, specifično visoka ulaganja su određena lokacijom spremnika i pogonskim iskustvom. Bez značajnih subvencija projekt neće moći biti realiziran.

Ugljikov dioksid se u dubokom slanom vodonosniku sprema na nekoliko načina [10]:

— u obliku peraste strukture, plinovite perjanice na vrhu vodonosnika, slično akumulaciji nafte ili plina ispod brtveće kape nepropusnih stijena, čije rasprostiranje traje preko 1 000 godina (!) i to obično pet do dvanaest kilometara od utisne bušotine (pouzdanost matematičkog modela predviđanja je dvojbena),
— kao mjehurići zarobljeni u prostoru pora nakon prolaska glavnine protoka,
— otapanjem u slanom vodonosniku poput šećera u čaju,
— kao istaloženi karbonatni mineral nastao geokemijskim reakcijama između CO_2, vode iz vodonosnika i stijena.

Brojne studije su pokazale da se tijekom utiskivanja CO_2, do 30 % CO_2otapa u slanoj vodi. Budući da je CO_2 lakši od slane vode, preostali CO_2 će plivati na vrhu slane vode i postupno se akumulirati. Kasnije se dio akumuliranog CO_2 otapa ili reagira s okolnim stijenama. Perasta struktura iznad vodonosnika se otapa više od tisuću godina! Značajniji efekti geokemijskih reakcija, zbrinutog CO_2, se uočavaju nakon nekoliko tisuća godina. Gdje nema stratigrafske ili strukturne zamke CO_2 se širi, prema matematičkim modelima, na velike površine i to desetinama i stotinama kvadratnih kilometara (!) ovisno o debljini slanog vodonosnika, poroznosti i propusnosti, reljefa brtveće kape i utisnutog volumena. Praćenje i utvrđivanje propuštanja spremljenog CO_2 u slani vodonosnik je veoma složeno. Spekulativna opcija je injektiranje pripremljene otopine CO_2 u slanoj vodi tako da bi se izbjegla mogućnost stvaranja peraste strukture. Procjene potencija-

deposit. About 1 Mt CO_2 have been stored annually since 1996. The storage is technically completely justified. Expected flows of carbon dioxide towards the surface have been observed and no leakages. The specific investment (compression and injection) amounted to 80 USD/t CO_2. Even after several tests, it is impossible to estimate accurately the storage potential (the potential of the remaining free pores). Conservative estimates fluctuated at about 2 % of volume unit capacity but later research showed that with lower costs, between 13 % and 68 % of volume units could be used under the condition that the right number and arrangement of boreholes were chosen. The new Norwegian project of Snøhvit (compression, transport and injection) is estimated at 275 USD/t CO_2; the largest part of the investment relates to compression and transportation, and specifically high investments are conditioned by the location of the reservoir and the experience of the operation. Without significant investment, it will be impossible to realize the project.

In the deep saline aquifer, carbon dioxide is stored in several ways [10]:

— in a feather-structured form, gas plume at the top of the aquifer, similar to oil or gas accumulation under the sealing cap of non-porous rocks, and their spreading lasts over 1 000 years (!) and that usually being five to twelve kilometres from the injection borehole (the reliability of the mathematical prediction model is uncertain),
— as bubbles captivated in the pore space after the passage of the majority of the flow,
— by solution in the saline aquifer like sugar in tea,
— as settled carbonate mineral arising from geochemical reactions between CO_2, water from aquifers and rocks.

Numerous studies have shown that at injection of CO_2, up to 30 % CO_2 dissolves in saline water. As CO_2 is lighter than saline water, the remaining CO_2 will float on top of the saline water and gradually accumulate. Later on, part of the accumulated CO_2 dissolves or reacts with the surrounding rocks. The feathery structure above the aquifer dissolves for more than a thousand years! More significant effects of geochemical reactions of the disposed CO_2 are visible after several thousand years. Where there is no stratigraphic or structural trap, CO_2 spreads, according to mathematical models, onto large surfaces and that for tens and hundreds of square kilometres (!) depending on the thickness of the saline aquifer, the porosity and the permeability, the sealant cap relief and the injected volume. The supervision and determining of the leakage of the CO_2 stored in the saline aquifer is very complex. A speculative option is the injection of the prepared solution of CO_2 in the saline water so as to avoid la skladištenja CO_2 u duboke slane vodonosnike oscilira ovisno o metodologiji, podacima i ostalim čimbenicima i kreće se do 10 000 Gt.

Temperaturni profil podzemnih sedimenata je veoma različit po lokacijama, jer oscilira geotermalni gradijent i temperatura površine stijena u dubokim slojevima. Stanje CO_2 pod zemljom će varirati i biti određeno gustoćom pri lokalnom tlaku. To utječe na potencijal skladišta po jedinici površine i određuje mehanizam propuštanja.

Iz ugljenom ložene termoelektrane električne snage od 500 MW treba spremiti oko 3 000 kt CO_2 po godini. Uz pretpostavku da CO_2 gustoće 0,5 t/m^3 može biti spremljen u slani vodonosnik pri njegovoj efektivnoj debljini od 1 metra, tijekom jedne godine pogona elektrane je potrebno 6 km^2 slanog vodonosnika za skladištenje emisije CO_2. Tijekom životnog vijeka od 40 godina potrebna je površina od 240 km^2 za skladištenje CO_2. Za spremanje emisije od 16 Gt CO_2 godišnje, oko 60 % godišnje svjetske emisije, je potrebno osigurati skladište površine poput Nizozemske.

5.5 Druge mogućnosti skladištenja u elektroenergetskom sektoru

Predlažu se brojne opcije skladištenja od kojih je jedino vrijedno napraviti kratak osvrt, prema procjeni autora članka, na spekulativne mogućnosti skladištenja u kupke vapnenca, površinsku mineralizaciju i skladištenje u oceane. Navedene mogućnosti skladištenja su generalno po opsegu angažiranja tvari za proces izvanredno zahtjevne, imaju vrlo veliku vlastitu potrošnju, mogućnost nadzora kroz tisuće godina je dvojbena kao i saniranje mogućih poremećaja u spremnicima.

Koncept vapnenačkih kupki je kombinacija hvatanja i spremanja. Kroz kupku, u kojoj je vapnenac otopljen u vodi, struje dimni plinovi iz kojih ugljikov dioksid reagira s vapnencem. Preliminarne procjene, iz više izvora informacija, ukupni trošak hvatanja i spremanja procjenjuju na oko 25 USD/t CO_2. Ovaj proces nije u dovoljnoj mjeri provjeren na pilot postrojenjima. Veći broj stručnjaka je uvjeren da je nemoguće proizvesti dovoljno male mjehuriće dimnog plina, potrebna je izuzetno velika površina reakcije, jer je transport CO_2 kroz otopljeni karbonat ograničavajući faktor te da će i velike dimenzija kupke vapnenca (smještaj opreme) biti limitirajući faktor.

Koncept površinske mineralizacije se temelji na reakciji magnezija iz tla i/ili kalcija silikatnih/eruptivnih stijena s CO_2 u karbonate. Slabo kisela otopina CO_2 u slanoj vodi može reagirati s mineralima okolnih stijena stvarajući navlake novih minerala. Brzinu procesa određuje kemijski sastav stijena i voda. Značajna količina tvari je

the possibility of formation of the feathery structure. Estimate of the potential for the storage of CO_2 in deep saline aquifers oscillates depending on the methodology, data and other factors and fluctuates up to 10 000 Gt.

The temperature profile of the underground sediments varies significantly from location to location because the geothermal gradient and the temperature of the rock surface in deep layers oscillate. Underground CO_2 states will vary and be determined by the density at local pressure. That affects the storage potential per surface unit and determines the leakage mechanism.

From a coal-fired thermal power plant of 500 MW (electric) about 3 000 kt CO_2 should be stored per year. Under the presumption that CO_2 with the density of 0,5 t/m^3 can be stored in deep saline aquifers at its actual thickness of 1 metre, during one year of the power plant's operation, 6 km^2 of saline aquifer are necessary for storage of the CO_2 emission. During a life cycle of 40 years, a surface of 240 km^2 is necessary for the storage of CO_2. For the storage of the emission of 16 Gt CO_2 per year, which is about 60 % of the annual world emission, it is necessary to ensure room for storage with the surface as great as the Netherlands.

5.5 Other storage options in the electric power system

Numerous options are suggested of which the only that are worth the observation, according to the judgement of the author of the article, are the speculative options of storage in limestone baths, superficial mineralization and storage in oceans. The above storage options are generally, according to the scope of substance employment for the process, extremely demanding, have very high own consumption, the possibility of supervision over thousands of years is uncertain as well as the restoration of possible disruptions in the reservoirs.

The limestone bath concept is a combination of capture and storage. Flue gases circulatethrough the bath, in which the limestone is dissolved in water, and the carbon dioxide from these gases reacts with the limestone. Preliminary estimates, from several data sources, set the total capture and storage cost at about 25 USD/t CO_2. This process has not been tested enough on pilot plants. Many experts are convinced that it is impossible to produce flue gas bubbles which are small enough, and that an extremely large reaction surface is necessary because the CO_2 transport through the dissolved carbonate is a limiting factor and that large limestone bath dimensions (equipment location) will also be a limiting factor.

The superficial mineralization concept is based on the reaction of the magnesium from the ground and/

uključena u proces, npr. uklanjanje CO_2 iz ugljenom loženog bloka električne snage od 500 MW proizvodi 30 kt magnezijevog karbonata tijekom dana (oko 1 000 kamiona!). Egzotermni proces vezivanja je testiran samo laboratorijski. Određeni tipovi podobnih eruptivnih stijena (obično nisu u sedimentima ležišta iz kojih se vade fosilna goriva) su razbacani širom svijeta, a sadrže 40 % do 50 % MgO i CaO. Za spremanje jedne tone CO_2 treba 0,9 t MgO; pri čemu se stvara oko 2,8 t otpada. Glavna zapreka, iz inženjerske perspektive gledano, je kinetika reakcije. Niti jedan tehnološki proces površinske mineralizacije nije koncipiran na stvarnim brzinama reakcije. Kruti otpad, koji se stvara u velikim količinama je potrebno ukloniti iz procesa i obraditi prije zbrinjavanja; razmjeri pothvata su poput izgradnje piramida u Egiptu. Očekivanja komercijalne primjene se temelje na procjenama spremanja od 30 USD/t CO_2 (hvatanje i transport su isključeni). Potrebno je optimirati troškove transporta silikatnih materijala do izvora emisije CO_2 ili lokacije spremanja. Proces je interesantan ukoliko ne postoje druge mogućnost uskladištenja. Neki stručnjaci smatraju da tehnološki proces nema budućnosti, osim možda nekih modificiranih postupaka temeljenih na otpadnom građevinskom betonu. Nepouzdan optimum procesa površinske mineralizacije se postiže pri tlaku od 1 bar i temperaturi od oko 350 °C, premda treba izvesti još niz opita (kinetika, katalizatori itd.)

Skladištenje CO_2 u oceane je kontraverzna opcija koja može biti provedena:

— otapanjem u morskoj vodi i spremanjem CO_2 u obliku hidrata i
— spremanjem tekućeg CO_2 na morske dubine veće od 4 000 m.

Većina tehnoloških postupaka uskladištenja na velikim dubinama oceana je provjerena u praksi. Međutim, vrlo malo je poznat utjecaj porasta koncentracije CO_2 na ekosustav oceana. Pilot projekti na Havaima i u Norveškoj su otkazani zbog prosvjeda ekologa. Japan smatra da bi opcija zbrinjavanja u oceane bila za njih poželjna, budući da ne raspolažu dovoljnim kapacitetom spremanja CO_2 u tlo. Rezultati proračuna matematičkim modelima navode da bi 80 % do 90 % spremljenog CO_2, na dubini od 3 000 m, trebalo biti trajno zadržano u oceanima za više od 500 godina. Na dubinama od 1 000 m zadržano bi bilo 30 % do 80 % spremljenog CO_2. To znači da dubina skladišta određuje količinu oslobođenog i reapsorbiranog CO_2 u atmosferu. Istjecanje CO_2 iz nedovoljno dubokih spremnika izravno utječe na ekosustav oceana kroz promjenu kiselosti vode, što se smatra glavnom preprekom. Morala bi se neutralizirati karbonska ki-

or calcium of the silicate/eruptive rocks with CO_2 in the carbonates. In saline water, the mildly acid CO_2 solution may react with the minerals of the surrounding rocks creating new mineral casings. The speed of the process is determined by the chemical composition of rocks and water. The process includes a number of substances, for example, the removal of CO_2 from the coal-fired block with the power of 500 MW produces 30 kt of magnesium carbonate during one day (about 1 000 trucks!). The exothermal bonding process has undergone laboratorial tests only. Certain types of eligible eruptive rocks (these are usually not in the sediments of the deposits from which fossil fuels are extracted) are dispersed all over the world and contain 40 % up to 50 % of MgO i CaO. The storage of one ton of CO_2 requires 0,9 t MgO; whereat about 2,8 t of waste is generated. The main obstacle, viewed from the engineering perspective, is reaction kinetics. None of the technological processes of superficial mineralization are conceived on actual reaction speeds. Crude waste, which is generated in large quantities, needs to be removed from the process and analysed before disposal; proportions of the project are like the construction of the pyramids of Egypt. Commercial application expectations are based on storage estimates of 30 USD/t CO_2 (exclusive of capture and transport). Silicate materials transport costs should be optimized up to the CO_2 emission source or to the storage location. The process is interesting if there are no other storage options available. Some experts believe that the technological process has no future, except maybe for some modified procedures based on waste construction concrete. The unreliable optimum of the superficial mineralization process is achieved at the pressure of 1 bar and a temperature of about 350 °C, however, several more tests still need to be undertaken (kinetics, catalysts, etc.).

Storage of CO_2 in oceans is a controversial option which can be performed:

— by dissolution in saline water and storage of CO_2 in the form of hydrates and
— by storage of liquid CO_2 at sea depths greater than 4 000 m.

Most technological storage processes at great ocean depths have been tested in practice. However, the impact of increased CO_2 concentration on the ocean ecosystem is slightly known. Pilot projects in Hawaii and in Norway were cancelled due to environmentalists' protests. Japan believes that the option of storage in oceans would be desirable for them because they do not avail of sufficient capacities for the underground storage of CO_2. Results of calculations by virtue of mathematical models state that 80 % up to 90 % of stored CO_2 at the depth of 3 000 m should be permanently kept in oceans for more than 500 years. At the depths of 1 000 m, 30 % up to 80 % of stored CO_2 would be kept permanently. That means selina vapnencem ili nekim drugim kemijskim dodatkom (baferom), jer bi u protivnom dodatne tisuće gigatona ugljika u oceanima proizvodilo značajne kemijske smetnje velikih razmjera. Nužna su dalja istraživanja radi boljeg razumijevanja procesa spremanja CO_2 u dubokim oceanskim vodama.

6 TRAJNOST I POUZDANOST SPREMNIKA I NADZOR

Dva tipa rizika su vezana za propuštanje CO_2 spremnika: lokalni specifičan za zdravlje, sigurnost i okoliš, te globalni vezan za vraćanje spremljenog CO_2 u atmosferu. Uzme li se u razmatranje samo globalni rizik, čini se da bi propuštanje do 0,1 % godišnje bilo prihvatljivo. Ono bi trebalo biti gornja granica u dozvoli za pogon; tehnička struka očekuje u stvarnim uvjetima rada daleko manja propuštanja. Vrlo veliki broj iznenađenja je moguć od spremljenog ugljikovog dioksida, promjene su vrlo spore, teško uočljive, a još teže ih je zaustaviti [11]. 20 % do 30 % veća koncentracija od normalne je fatalna za faunu. Prirodna katastrofa izbijanja ugljikovog dioksida nakon potresa i vulkanskih erupcija mogu biti indikativna i za incidente na sustavima HITS CO_2. Za zagađenje s CO_2 indicije su kod podzemnih voda smanjivanje PH vrijednosti, pojava teških metala u vodi za piće, kontaminacija površinskih voda, oksidacija osjetljivih tvari, i slično. Podzemni spremnici CO_2 mogu inicirati vrlo nepovoljne seizmičke aktivnosti slične onima kod sezonskih spremnika prirodnog plina. Velika su nepoznanica propuštanja brtvi (od cementa) na spremnicima CO_2. Mineralne vode koje izbijaju iz slanih vodonosnika reduciraju vrijeme zadržavanja spremljenog CO_2 [9] sa 7 000 godina na 2 000 godina. Potrebno je mnogo više pokusnih postrojenja za potpuniju procjenu trajnosti spremanja i to naročito za odlaganje u duboke slane vodonosnike. Nužan je i razvoj kriterija odabira lokacija, prije nego bude bilo moguće nominirati neku od njih i utvrditi odgovarajuće postupke trajnog nadzora nad skladištem. Ukoliko bi bio stabiliziran (dogovorom) limit koncentracije na 450 ppmv CO_2 u atmosferi, s ciljem njegovog održavanja, ugljikov dioksid bi trebalo zadržati oko 7 000 godina u spremnicima, dobiven iz preostalih rezervi ugljena i to uz prihvatljivo propuštanje [2].

Spremnike s pohranjenim ugljikovim dioksidom je nužno nadzirati stotinama, a u nekim slučajevima i tisućama godina zbog spore geokemijske reakcije. Sljedeće teme povezane s faktorom rizika su predmet istraživanja:

that the storage depth determines the quantity of CO_2 released and re-absorbed into the atmosphere. Leakage of CO_2 from insufficiently deep reservoirs directly impacts the ocean ecosystem through the change of water acidity and this is considered to be the greatest obstacle. Carbonic acid should be neutralized by limestone or some other chemical adjuvant (buffer) because, in the contrary, additional thousands of gigatons of carbon in the oceans would produce significant and extensive chemical disruptions. Further research is necessary for the purpose of better understanding of the process of storage of CO_2 into deep ocean waters.

6 DURATION/RELIABILITY OF THE RESERVOIR AND ITS SUPERVISION

Two types of risks are related to CO_2 reservoir leakage: local, related to health, safety and the environment, and the global, related to the return of the stored CO_2 into the atmosphere. If only global risk is taken into observation, it seems that annual leakage of up to 0,1 % would be acceptable. It should be the top limit in the operation permit; in actual working conditions, the technical profession expects far less leakage. Many surprises are possible to happen with stored carbon dioxide; changes are slow, hardly visible and even harder to be stopped [11]. A concentration higher by 20 % up to 30 % than normal is fatal for the fauna. The natural disaster of carbon dioxide bursts after earthquakes and volcano eruptions could be indicative for CITS CO_2 system incidents as well. In underground waters, reduced PH value, presence of heavy metals in drinking water, contamination of surface waters, oxidation of sensitive substances, etc. indicate CO_2 pollution. Underground CO_2 reservoirs may initiate very unfavourable seismic activities similar to those in seasonal natural gas reservoirs. Sealant (made of concrete) leakages on CO_2 reservoirs are an unknown. Mineral waters which emerge from the saline aquifers reduce the time the stored CO_2 is kept [9] from 7 000 years to 2 000 years. Many more test plants are necessary to make a fuller estimate of storage permanency and that particularly for disposals into deep saline aquifers. The development of the location selection should be undertaken before some of them can be nominated and adequate procedures of constant storage supervision can be determined. If the concentration limit is to be stabilized (by agreement) at 450 ppmv CO_2 in the atmosphere, for the purpose of its maintenance, carbon dioxide should be kept for about 7 000 years in the reservoirs. The carbon dioxide should be gained from the remaining coal reserves and the leakage should be acceptable [2].

Reservoirs with stored carbon dioxide have to be supervised for hundreds, and, in some cases, for tho-

- studiranje fizikalnih i kemijskih procesa u spremnicima,
- postupci i kriteriji odabira ležišta, uključujući i analize seizmičkih aktivnosti,
- metode predskazivanja dugoročnog ponašanja CO_2 u podzemlju,
- tehnike i metode nadgledanja i provjere,
- procjene rizika i upravljanje rizicima,
- postupci i normativi sigurnosti,
- integritet ispravnosti bušotina.

Nameće se zaključak da su tehnološki postupci hvatanja i izdvajanja bliži komercijalizaciji od postupaka skladištenja i nadzora nad skladišnima, jer je kod njih daleko veći broj nedovoljno istraženih korelacija koje bitno utječu na sigurnost uskladištenog ugljikovog dioksida.

7 PROIZVODNJA GORIVA I KEMIKALIJA IZ CO_2

Na prvi pogled izgleda da ne bi mogla zaživjeti proizvodnja goriva za transportna sredstva iz CO_2. Međutim, zasada samo iz energetske perspektive, smisla ima ako na jednoj lokaciji postoji višak čiste energije proizvedene iz nuklearnih ili obnovljivih izvora, a na drugoj postoji potreba za energijom. CO_2 bi se tada transportirao brodovima iz jedne regije u drugu, dok bi se ugljikovodična goriva (metanol i dimetil eter - DME) transportirala u suprotnom pravcu. Obnovljivi izvor ugljika, poput biomase, je potreban za proizvodnju metanola i DME koji su znatno jeftiniji od vodika ili elektro-akumulatora namijenjenih transportu. Trenutačno ne postoje na tržištu plinske turbine koje mogu u dugotrajnom pogonu spaljivati čisti vodik. Problem su visoka lokalna naprezanja materijala glavnih komponenti izloženih plamenu vodika.

Značajnom smanjenju ukupne emisije CO_2 može doprinijeti proizvodnja metanola i DME iz recikliranog CO_2 (uhvaćen i izdvojen) iz dimnih plinova tijekom spaljivanja biomase:
$CO_2 + 3H_2 \rightarrow CH_3OH$.

Ako se metanol koristi za proizvodnju transportnih goriva, tada je redukcija emisije CO_2 oko 3,14 t po 1 Gt supstituiranog goriva za transport. Po toni metanola je potrebno uložiti 28 GJ električne energije! Očito su u pitanju vrlo skupa goriva za koja bi trebalo provjeriti opravdanost masovne proizvodnje.

usands of years because of the slow geochemical reaction. The following subjects related to the risk factor are the subject of research:

- studying physical and chemical processes in the reservoirs,
- procedures and criteria for choice of deposits, including the analyses of seismic activities,
- long-term CO_2 underground behaviour prediction methods;
- supervision and control techniques and methods,
- risk assessments and risk management,
- safety procedures and standards,
- borehole operation integrity.

The conclusion seems to be that technological capture and isolation procedures are much closer to commercialization than the storage and storage supervision procedures because they include a much larger number of insufficiently researched correlations which significantly impact the safety of the stored carbon dioxide.

7 PRODUCTION OF FUEL AND CHEMICALS FROM CO_2

At first glance, it seems that production of fuel from CO_2 for means of transportation could not take hold. However, for now only from the energy perspective, it makes sense only if in one location there is excessive pure energy produced form nuclear or renewable sources and if in the other location there is a need for energy. CO_2 would then be transported by ships form one region to another, while hydrocarbon fuels (methanol and dimethyl ether - DME) would be transported in the opposite direction. A renewable coal source, such as biomass, is necessary for the production of methanol and DME which are much cheaper than hydrogen or electric accumulator batteries intended for transport. At the moment, there are no gas turbines on the market which can, in long-term operation, burn pure hydrogen. The problem are high local stresses of the materials of the main components exposed to hydrogen flames.

The production of methanol and DME from recycled CO_2 (captured and isolated) from flue gases during the burning of biomass can contribute to a significant reduction of the total emission of CO_2:
$CO_2 + 3H_2 \rightarrow CH_3OH$.

If methanol is used for the production of transport fuels, then the CO_2 emission reduction is about 3,14 t per 1 Gt of substituted transport fuel. Per one ton of methanol, 28 GJ of electricity need to be put in! The issue at hand are obviously expensive fuels for which the justifiability of mass production should be verified.

8 TROŠKOVI HITS-a

Pouzdanih procjena o ukupnim troškovima HITS-a kao i o pojedinim troškovima tehnološkog lanca nema. Većina tehnologija nije provjerena na demonstracijskim postrojenjima velikih jediničnih kapaciteta, već je samo pokazano njihovo zadovoljavajuće funkcioniranje na pilot postrojenjima (tablica 5).

Europska unija ima uspostavljen sustav trgovanja emisijskim jedinicama stakleničkih plinova (EU-ETS), u okviru kojeg se utvrđuju dopuštene razine emisija za industrije i uspostavlja sustav trgovanja emisijskim dozvolama. Cijena emisijske dozvole na tržištu je iznosila oko 15 EUR/t u prosincu 2008. godine. Pri ovakvoj cijeni dozvola za emisiju, ne isplati se aktivirati projekte izgradnje HITS-a, jer isti nisu ekonomski samoodrživi. Trenutačno se može vrlo grubo, zbog velikog broja opcija, procijeniti da bi ukupni trošak HITS tehnologije bio unutar 50 USD/t CO_2 do 100 USD/t CO_2 smanjenog emitiranja. Sve dok ne bude postignuta ekonomska samoodrživost HITS-a nužni će biti financijski poticaji. Prije početka krize globalnog gospodarstva, koncem 2008. godine Europska unija je imala nacrt prijedloga plana ulaganja u energetiku reda veličine 200 milijardi eura do 2030. godine. Ista bi bila, uz utjecaje na druge tržišne mehanizme, usmjerena na istraživanja, razvoj i komercijalizaciju termoenergetskih izvora nove generacije loženih fosilnim gorivom ukupne električne snage od 40 000 MW.

Smatra se da bi do 2030. troškovi HITS-a trebali biti smanjeni na 25 USD/t CO_2 do 50 USD/t CO_2 i postati ekonomski atraktivni, to jest biti niži od cijena jedne emisijske dozvole koja se mora osigurati za pogon termoelektrane bez HITS-a

Hvatanje CO_2 je dominirajuće u ukupnom trošku. Ukoliko se uzme u račun buduća povećana efikasnost, trošak hvatanja može biti smanjen sa sadašnjih procijenjenih od 50 USD/t CO_2 na oko 10 USD/t CO_2 do 25 USD/t CO_2 za loženje ugljenom i do 25 USD/t CO_2 do 30 USD/t CO_2 za plinom ložene termoenergetske proizvodne jedinice.

Troškovi transporta CO_2 po toni više ovise o volumenu koji se transportira, a manje od udaljenosti. Za cijevni transport količina većih od 1 000 kt CO_2 godišnje na udaljenosti veće od 500 km procjenjuju se troškovi transporta u rasponu od 1 USD/t CO_2 do 10 USD/t CO_2. Injektiranje CO_2 se procjenjuje na 2 USD/t CO_2 i to za količinu od 1 000 kt u slane vodonosnike, te do 50 USD/t CO_2 ECBM projekte.

8 CITS COSTS

There are no reliable estimates of total CITS costs as well as of particular costs of the technological chain. Most technologies have not been tested on demonstration plants of large unit capacities – their satisfactory operation has only been shown on pilot plants (Table 5).

The European Union has set up a system of trade in greenhouse gas emission units (EU-ETS), within which allowed emission levels for industries are determined and the system of trade in emission permits is set up. The price of emission permit on the market amounted to about 15 EUR/t in December 2008. With this price of emission permits, it is not cost-effective to activate CITS construction projects because they are not economically self-sustainable. At the moment, it is possible to estimate very roughly, due to a high number of options, that the total cost of the CITS technology would be between 50 USD/t CO_2 and 100 USD/t CO_2 of reduced emission. Until economic self-sustainability of the CITS is achieved, financial incentives will be necessary. Before the global economy crisis began, at the end of 2008, the European Union had a draft proposal of the energy investment plan at the amount of 200 billion euros until 2030. Along with impacting other trade mechanisms, it would be focused on research, development and commercialization of thermal energy sources of the new generation fired by fossil fuels of total power of 40 000 MW (electric).

It is believed that by 2030, CITS costs should fall to between 25 USD/t CO_2 and 50 USD/t CO_2 and become economically attractive, that is, become lower than the prices of an emission permit which is to be ensured for the operation of a thermal power plant without the CITS.

CO_2 capture is dominant item in the total cost. If the future increased efficiency is taken into account, the capture cost can fall from the today's estimate of 50 USD/t CO_2 to about 10 USD/t CO_2 up to 25 USD/t CO_2 for coal-firing and to 25 USD/t CO_2 up to 30 USD/t CO_2 for gas-fired thermal power production units.

CO_2 transportation costs per ton depend more on the volume of the transport and less on the distance. For pipeline transport of annual amounts larger than 1 000 kt CO_2 to distances higher than 500 km transportation costs are estimated in the range between 1 USD/t CO_2 and 10 USD/t CO_2. CO_2 injection is estimated at 2 USD/t CO_2 and that for the quantity of 1 000 kt in saline aquifer, and up to 50 USD/t CO_2 for ECBM projects.

Part of the CITS costs can be covered by income from increased fossil fuels extract efficiency. In certain specific projects, income could reach as

Dio troškova HITS može biti pokriven prihodima od povećane efikasnosti vađenja (iscrpka) fosilnih goriva. U nekim specifičnim projektima mogu prihodi dosegnuti i do 50 USD/t CO_2. Za neke od pripremljenih tehnologija HITS-a procjenjuje se da bi troškovi proizvodnje električne energije trebali biti povećani za 1 USc/kWh do 2 USc/kWh.

Članice EU su postavile sljedeće istraživačko razvojni prioriteti:

— hvatanje CO_2 i proizvodnja vodika iz plinovitih fosilnih goriva,
— nadziranje i verificiranje geoloških spremnika,
— priprema masovne proizvodnje vodika iz dekarboniziranih fosilnih goriva uključujući i geološke spremnike,
— napredne tehnike hvatanja i izdvajanja,
— obilježavanje i karakterizacija potencijalnih geoloških spremnika, usklađivanje izvora i ponora,
— koordinacija i izrada mrežnih planova aktivnosti za HITS.

Predloženo je, 2008. godine, od parlamentarne grupe EU Parlamenta da za nove termoelektrane, kapaciteta većeg od 300 MW, nakon 2015. godine najveća dozvoljena prosječna godišnja emisija CO_2 bude 500 g/kWh. To znači da bi bilo dozvoljeno graditi bez HITS samo termoelektrane ložene prirodnim plinom jer je na današnjem razvoju tehnike tipična emisija za loženje ugljena između 700 g/kWh i 850 g/kWh, a za tekuće gorivo 590 g/kWh.

much as 50 USD/t CO_2. For some of the prepared CITS technologies, the increase of electricity production costs is estimated at 1 USc/kWh up to 2 USc/kWh.

EU member states have established the following research and development priorities:

— CO_2 capture and production of hydrogen from gaseous fossil fuels,
— supervision and verification of geological reservoirs,
— preparation of mass production of hydrogen from decarbonised fossil fuels including geological reservoirs,
— advanced capture and isolation technologies,
— marking and characterization of potential geological reservoirs, harmonization of sources and sinks,
— coordination and elaboration of network plans for the CITS activities.

In 2008, a EU Parliament group suggested that for new thermal power plants with a capacity of more than 300 MW, after the year 2015, the maximum allowed average annual CO_2 emission should be 500 g/kWh. That means that it would be allowed to construct, without CITS, only thermal power plants fired by natural gas because at today's level of technical development, the typical emission at coal firing is between 700 g/kWh and 850 g/kWh, and for liquid fuels it is 590 g/kWh.

Tablica 5 – Pregled trenutačne tržišne zrelosti sastavnica sustava HITS-a [4]
Table 5 – Overview of the current market maturity of the CITS system components [4]

HITS sastavnica / CITS component	Tehnologija / Technology	Razvoj / Development	Demonstracijska faza / Demonstration phase	Uvjetno ekonomski opravdano / Conditionally economically justified	Na tržišnu provjereno / Market-tested
Hvatanje / Capture	Nakon izgaranja / Post-combustion			X	
	Prije izgaranja / Pre-combustion			X	
	Izgaranje u struji kisika / Oxyfuel		X		
	Industrijske separacije (procesiranje prirodnog plina, proizvodnja amonijaka) / Industrial separations (processing natural gas, ammonium production)				X
Transport / Transport	Cjevovodima / By pipelines				X
	Brodovima / By ships			X	
Podzemno spremanje / Underground storage	Povećanje iscrpka nafte utiskivanjem / Enhanced oil recovery by injection				X*
	Povećanja iscrpka plina utiskivanjem / Enhanced gas recovery by injection			X	
	Otplinjavanje (metana) ležišta ugljena / Coal bed (methane) degassing		X		
	Iskorištena naftna ili plinska polja / Depleted oil or gas fields			X	
	slani vodonosnik / saline aquifer			X	
Spremanje u oceane / Storage in oceans	Direktno injektiranje – otopina / Direct injection – solution	X			
	Direktno injektiranje – tekuće stanje / Direct injection – liquid state	X			
Mineralizacija / Mineralization	Silikati / Silicates	X			
	Kruti otpad / Crude waste		X		
Industrijska namjena / Industrial use					X

Napomena: EOR je tržišno konkurentna tehnologija za povećanje iscrpka, ali i uvjetno opravdana ukoliko bude korištena primarno za spremanje CO_2
Remark: The EOR is a market-competitive technology for enhanced recovery but it is also conditionally justified if it is used for primary storage of CO_2.

9 ZAKLJUČAK

Izgaranje ugljena je odgovorno za 71 % emisije CO_2, prirodni plin za 18 % a loživo ulje za 11 % [12]. Povijesno gledano ljudska civilizacija je izgaranjem fosilnih goriva od 1751. do 2002. godine dostigla zbirnu emisiju u Zemljinu atmosferu od oko 1 000 Gt CO_2, dok će u idućih 28 godina prema nekim projekcijama [3], ukoliko ne dođe do promjene globalne energetske politike emitirati još 750 Gt CO_2 (!). Očito je da su potrebna veoma velika financijska ulaganja u razvoj novih projekata i poticanje paralelnih industrijskih i akademskih inicijativa te što veći broj tehničkih demonstracija tehnologija čija je vjerojatnost primjene izgledna na postrojenjima industrijskih razmjera.

Velika očekivanja se polažu u dobre rezultate pogona, do 2020. godine, HITS postrojenja koja će biti implementirana u novim termoenergetskim i kemijskim kompleksima u Alžiru (Salah), Velikoj Britaniji (Peterhead), USA-u (Carson), Australiji (Kwinana) i Norveškoj (Sleipner) [13]. U njima će rasplinjavanjem prirodnog plina biti proizvedena električna energija, vodik za dalje korištenje u energetici i transportu, a uhvaćeni, izdvojeni i transportirani ugljikov dioksid će biti spremljen u bušotine plina u neposrednoj blizini.

Za čisti ugljen bez emisije ugljikovog dioksid trebat će nešto duže vremena, jer je nužno ubrzati razvoj novih materijala koji bi trebali izdržati dugogodišnja toplinska naprezanja na visokim temperaturama pregrijane pare od 700 °C i postići neto učinak postrojenja iznad 50 % u trajnom pogonu.

Globalni problem, na koji danas nema zadovoljavajućih odgovora, bit će transport i nadzor skladišta ugljikovog dioksida velikih razmjera i to do oko 10 Gt CO_2 godišnje. Uočena propuštanja, često s velikim vremenskim kašnjenjem, neće moći biti otklonjena promptno, već u dužem periodu ili nikada. Zbog toga je nužno snažno politički podržati i financirati napore u razvoju, istraživanju i primjeni novih tehnoloških koncepcija i izbjeći, ili bar usporiti, katastrofalne posljedice klimatskih promjena koje se uočavaju zadnjih desetljeća.

9 CONCLUSION

Coal combustion accounts for 71 % of CO_2 emission, natural gas for 18 % and heating oil for 11 % [12]. Viewed historically, by combustion of fossil fuels from 1751 to 2002, human civilization has reached an aggregate emission into the Earth's atmosphere of about 1 000 Gt CO_2, while in the next 28 years, according to some predictions [3], if no change occurs as regards the global energy policy, another 750 Gt CO_2 will be emitted (!). It is obvious that very extensive financial investments in the development of new projects and the stimulation of parallel industrial and academic initiatives are necessary, as well as a large number of technical demonstrations of the technologies the application of which will probably take place on plants of industrial dimensions.

The operations of the CITS plants that will be implemented in the new thermal power plants and chemical complexes in Algiers (Salah), Great Britain (Peterhead), USA (Carson), Australia (Kwinana) and Norway (Sleipner) [13] are expected to yield good results by 2020. There, by natural gas combustion, electricity will be produced, as well as hydrogen for further use in the energy/transport sector, and the captured, isolated and transported carbon dioxide will be stored into gas boreholes in the direct vicinity.

The obtainment of pure coal without carbon dioxide emission will take some more time because it is necessary to speed up the development of new materials which should endure years of thermal stress at high overheated vapour temperatures of 700 °C and achieve net plant output higher than 50 % in permanent operation.

The global problem, which cannot be answered today, will be the transport and supervision of carbon dioxide reservoirs of large dimensions and that being as much as 10 Gt CO_2 annually. It will be impossible to promptly remove the leakages observed, often with a delay in time, but in a longer period of time or never. It is therefore necessary for the policies to support adamantly and finance the efforts of the development, research and application of new technological concepts and to avoid, or at least slow down, catastrophic consequences of climatic changes which have been observed in the last decades.

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ANALIZA POJAVE NEGATIVNE CIJENE NA SPOT TRŽIŠTU ELEKTRIČNE ENERGIJE EUROPSKE BURZE ENERGIJE EEX

ANALYSIS OF THE OCCURRENCE OF THE NEGATIVE PRICE ON THE EUROPEAN ENERGY EXCHANGE (EEX) ELECTRICITY SPOT MARKET

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Europska burza energije EEX postala je, uz Nord Pool u nordijskim zemljama, najznačajnija burza energije u kontinentalnoj Europi. Cijene i prilike s EEX-a nerijetko predstavljaju referencu u trgovanju električnom energijom na lokalnim ili regionalnim tržištima europskih zemalja. U radu je prikazana i razmatrana pojava negativne cijene na spot tržištu električne energije na EEX-u krajem prosinca 2008. godine. Negativna cijena, kada je predviđena i dopuštena u strukturi tržišnog modela na burzi energije, odražava situaciju na tržištu u kojoj je ponuda značajno nadmašila potražnju. Premda je postizanje negativne cijene na tržištu električne energije više izuzetak nego pravilo, zanimljivo je sagledati što uzrokuje takve neobične pojave. Od njenog uvođenja na EEX-u negativna tržišna cijena postignuta je tek nekoliko puta, uglavnom u pojedinačnim satima noću kada je potrošnja električne energije u pravilu smanjena. Situacija analizirana u ovom radu zanimljiva je jer je negativna cijena postignuta u razdoblju od nekoliko uzastopnih sati te zbog postignutih iznosa negativne cijene, pa su u radu razmotreni mogući uzroci koji su do toga doveli. Budući da su europski elektroenergetski sustavi dobro povezani, provedena je analiza i u radu je predočeno kako su se razmatrana zbivanja u zapadnoj i središnjoj Europi odrazila na tokove električne energije u hrvatskom elektroenergetskom sustavu i njegovom okruženju.

The EEX (European Energy Exchange) has become, along with Nord Pool in Nordic countries, the most significant energy exchange in continental Europe. EEX's prices and possibilities often represent a reference in the electricity trade on the local or regional markets of European countries. The work also shows and deliberates on the occurrence of negative prices on the EEX electricity spot market at the end of December 2008. The negative price, when predicted and allowed in the market model structure at the energy exchange, mirrors the situation on the market in which the offer has significantly exceeded the demand. Although the achievement of the negative price on the electricity market is more of an exception than a rule, it is interesting to contemplate the reasons for such an unusual occurrence. Since its introduction onto the EEX, the negative market price has been achieved only a few times, mostly in particular hours at night when the consumption of electrical energy is normally reduced. The situation analysed in this work is interesting because the negative price was achieved in the period of a few successive hours and because of the achieved amounts of the negative price, so the work contemplates on possible causes which led to such a situation. Since European electrical power systems are well connected, an analysis has been performed and the work presents how the observed occurrences in western and middle Europe have impacted electricity flows in the Croatian electrical power system and its surroundings.

Ključne riječi: europska burza energije EEX; negativna cijena; spot tržište električne energije; tržišna cijena
Key words: electricity spot market; European Energy Exchange (EEX); market price; negative price

1 UVOD

Otvaranje tržišta električne energije u velikom broju europskih zemalja rezultiralo je s dva prevladavajuća načina trgovanja: putem bilateralnih ugovora (engl. *over the counter trading*, OTC *trading*) i putem organizirane burze električne energije (engl. *power exchange*). U prvom se slučaju svi uvjeti trgovanja dogovaraju između dviju ugovornih strana koje u potpunosti snose rizik međusobnog poslovanja. U drugom se slučaju trguje na organizirani i standardizirani način na središnjem mjestu trgovanja – burzi, gdje se prodavatelji i kupci anonimno susreću i sklapaju poslove posredstvom burze. U svakoj transakciji, bilo za prodaju bilo za kupnju električne energije, burza predstavlja drugu ugovornu stranu i preuzima rizik (engl. *counterparty risk*) te jamči fizičko i financijsko poravnanje (engl. *physical and financial clearing and settlement*). Burze električne energije su na početku svog poslovanja obično nudile trgovanje na spot tržištu dan unaprijed (engl. *spot electricity market, day-ahead electricity market*). Na spot tržištu se trguje električnom energijom koja se isporučuje sljedećeg dana i plaćanja se izvršavaju neposredno nakon obavljenog posla. S vremenom su, uobičajeno nakon uspješne uspostave spot tržišta, burze proširile svoju ponudu organizirajući financijsko tržište za električnu energiju na kojem se trguje izvedenicama tj. financijskim ugovorima (engl. *financial electricity market, derivatives electricity market*) koji pružaju mogućnost ograničavanja izloženosti riziku na tržištu. Mnoge od njih proširile su svoje poslovanje na druge energente i proizvode vezane uz energetiku (npr. prirodni plin, ugljen, emisije stakleničkih plinova) čime su se pretvorile u burze energije (engl. *energy exchanges*).

Uspostavom burzi i spot tržišta bilateralno trgovanje nije zanemareno, već se oba načina kupoprodaje električne energije istodobno i usporedno koriste. Na većini tržišta energije europskih zemalja najveći dio trgovine električnom energijom obavlja se dugoročnim bilateralnim ugovorima, dok se manji dio kratkoročne trgovine obavlja putem spot tržišta na burzi [1] i [2]. Bilateralnim se ugovorima obično podmiruju tzv. bazni i manje-više konstantni dijelovi dijagrama opterećenja (npr. blokovi noćne energije, blokovi dnevne vršne energije) za dulje vremensko razdoblje kao što su godina ili mjesec. Na spot tržištu se uobičajeno trguje manjim količinama električne energije za kraća vremenska razdoblja kao što su jedan sat ili blok od nekoliko sati, čime se nastoji popuniti preostali promjenjivi dio dijagrama opterećenja, jer se trguje u vremenu mnogo bližem isporuci kada se raspolaže s više boljih informacija i točnijim previđanjima. Trgovanje na razini sata, primjerice, omogućava tržišnim sudionicima da uravnoteže svoj portfelj kupnje i prodaje električne energije u

1 INTRODUCTION

The opening of the electricity market has resulted in two prevailing trading methods in a large number of European countries: by virtue of over-the-counter trading (OTC trading) and by virtue of organized power exchange. In the former case, all trading conditions are agreed upon between the contracting parties which undertake the full risk of interoperability. In the latter case, trading is done in an organized and standardized manner at the central place of trading - the exchange, where sellers and buyers anonymously meet and conclude transactions through the exchange. In each transaction, either for the sale or for the purchase of electricity, the exchange represents the other contracting party and undertakes the counterparty risk and guarantees physical and financial clearing and settlement. At their beginnings, energy exchanges usually offered day-ahead spot electricity market trading. The trading on the spot market included electricity which was delivered the following day and payments which were performed immediately after the executed transaction. In time, usually after a successful establishment of the spot market, exchanges have widened their offers by organizing the financial electricity market where trading in derivatives, that is, financial contracts, takes place and these enable the limitation of exposure to risk on the market. Many of them have widened their business onto other energy sources and products related to energy (e.g. natural gas, coal, greenhouse gas emissions) which transformed them into energy exchanges.

The establishment of exchanges and spot markets did not neglect over-the-counter trading - both methods of purchase of electricity are used simultaneously and in parallel. On most of the energy markets of the European countries, most of the trading in electricity is done by virtue of over-the-counter trading, while a minor part of short-term trading is done by virtue of the spot exchange on the market [1] and [2]. Over-the-counter trading usually serves to settle the so-called basic and more or less constant parts of the load diagram (e.g. night energy blocks, daily peak energy blocks) for longer intervals of time such as a year or a month. The spot market usually serves for trading in smaller amounts of electricity for shorter periods of time such as an hour or a block of a few hours with the purpose to fill the remaining alterable part of the load diagram because the trading is done in the period much closer to the delivery when operators avail of more better-quality information and more precise forecasts. Trading on the level of an hour, for example, enables market participants to balance their electricity purchase and sale portfolio in the particular hour, while a combination of trading at the određenom satu, dok se kombinacijom trgovanja na razini sata i blokovima energije može optimirati uporaba proizvodnih postrojenja. Neke burze organiziraju i tržište tijekom dana isporuke (engl. *intraday market*) koje tržišnim sudionicima daje mogućnost uravnoteženja njihove kupnje i prodaje električne energije u vremenu gotovo neposredno prije same isporuke (npr. 60, 75 ili 120 minuta prije isporuke). Na taj se način tržišnim sudionicima pruža fleksibilnost u trgovanju i ostvarenju ugovorenih obveza te daje prilika za smanjivanje troškova nerijetko skupe energije uravnoteženja, posebice u slučaju nepredviđenih događanja, kao što su neplanirane obustave rada ili ispadi iz pogona zbog kvarova postrojenja proizvođača ili krajnjih potrošača električne energije.

Osim već spomenute anonimnosti pri trgovanju, preuzimanja rizika te osiguravanja fizičkog i financijskog poravnanja, trgovanje putem burze pruža niz prednosti od kojih su najvažnije formiranje tržišne cijene (engl. *market clearing price)* i njena razvidnost te razvidnost ostalih informacija koje burza pruža tržišnim sudionicima. Cijena sa spot tržišta, ili kraće tržišna cijena, služi kao referenca za cijene na svim drugim tržištima kao što su financijsko tržište, bilateralno trgovanje, tržište energije uravnoteženja ili ugovaranje prodaje električne energije krajnjim potrošačima [1] i [2]. Nadalje, trend promjene tržišne cijene daje signale za buduća ulaganja u proizvodna postrojenja: rastući trend ukazuje na potrebu za ulaganjima, a padajući upravo obrnuto. Također, u razdoblju smanjene ili oskudne ponude električne energije velika tržišna cijena može potaći potrošače na smanjivanje njihove potrošnje.

U ovom je radu pozornost usmjerena na jedan detalj vezan uz tržišnu cijenu električne energije na spot tržištu europske burze energije EEX (engl. *European Energy Exchange*, EEX) koji je zabilježen krajem prosinca 2008. godine. Početkom četvrtog tjedna prosinca u nekoliko uzastopnih sati noću te za blokove energije tijekom noćnih sati tržišna cijena postigla je zamjetan negativan iznos. Tržišna cijena električne energije je uobičajeno pozitivnog iznosa i odražava uravnoteženost ponude i potražnje, odnosno prodaje (proizvodnje) i kupnje (potrošnje) električne energije. U takvoj situaciji kupac plaća prodavatelju kupljeni proizvod po tržišnoj cijeni. Negativna cijena znači da prodavatelj prodaje električnu energiju kupcu i za to plaća umjesto da biva plaćen. Ili, drugim riječima, kupac dobiva kupljenu energiju, ali istodobno, umjesto da plaća za proizvod, kupac dobiva i novac. Na temelju javno dostupnih podataka i informacija te saznanja autora u radu se nastojalo dati odgovore na pitanja kako se i zašto postigla negativna tržišna cijena. Usporedbe radi, u radu su razmatrana zbivanja u trećem i četvrtom tjednu prosinca 2008. godine.

level of an hour and in energy blocks can optimize the use of production facilities. Some exchanges also organize the intraday market which gives the market participants the possibility of adjustment of their purchase and sale of electricity in a period almost immediately before the delivery itself (e.g. 60, 75 or 120 minutes before delivery). This method provides market participants with flexibility in trading and realization of contracted obligations and a chance for reduction of costs of often very expensive balance energy, especially in the case of unforeseen events, such as unplanned work discontinuations or operation failures due to faults of the plant or end electricity consumers.

Besides the already mentioned anonymity at trading, undertaking of risk and provision of physical and financial settlement, trading through the exchange offers a number of advantages of which the most important are the market clearing price and its conspicuousness and the conspicuousness of the other information offered by the exchange to the market participants. The spot market price, or, shorter, the market price, serves as a reference for the prices on all the other markets such as the financial market, over-the-counter trading, balance energy trading or contracting the sale of electricity to end consumers [1] and [2]. Furthermore, the trend of market price alterations provides signals for future investments into production facilities: the growing trend points to a need for investments, and the falling trend exactly to the opposite. Moreover, in the period of reduced or sparse offer of electricity, a high market price may encourage consumers to reduce the consumption.

In this work, the focus is on one detail related to the electricity market price on the European Energy Exchange (EEX) which was recorded at the end of December 2008. At the beginning of the fourth week of December in several consecutive hours at night, as well as for energy blocks during night hours, the market price achieved a significant negative amount. The electricity market price is usually of positive amount and it represents the balance between offer and demand, that is, sale (production) and purchase (supply) of electricity. In such case the buyer pays the seller the purchased product at the market price. Negative price means that the seller sells (supplies) energy to the buyer and pays for it, instead of being paid for it. Or, in other words, the buyer gets (takes over) the purchased energy, but at the same time, instead of paying for the product, the buyer also gets the money. Based on publicly available data and information and the author's cognitions, the work aimed to provide answers to the questions about why and how was the negative market price achieved. For the purpose of comparison, the work reviews the events in the third and fourth week of December 2008.

U nastavku rada ukratko su opisani pravilo određivanja tržišne cijene koje prevladava u europskim zemljama te europska burza energije EEX, nakon čega slijedi razmatranje konkretne pojave negativne cijene. Na kraju rada predočena su događanja u hrvatskom elektroenergetskom sustavu (EES-u) krajem 2008. godine te kakav je bio utjecaj razmatrane situacije u zapadnoj i središnjoj Europi na tokove snaga u hrvatskom EES-u i njegovom neposrednom susjedstvu.

2 ODREĐIVANJE CIJENE NA SPOT TRŽIŠTU

Većina burzi trgovanje na spot tržištu organizira i provodi kroz središnju aukciju (dražbu) koja se održava nakon isteka vremena za podnošenje ponuda. Osim toga, neke burze za određene proizvode nude i tzv. kontinuirani način trgovanja (engl. *continuous trading*) u kojem se prispjele ponude odmah nalaze na tržištu. U tom načinu trgovanja kada se pronađu međusobno odgovarajuće ponude za kupnju i prodaju električne energije (engl. *matching bids*) one se odmah realiziraju. U aukcijskom (dražbenom) načinu trgovanja za izračunavanje tržišne cijene prevladava tzv. pravilo jedinstvene cijene (engl. *uniform price rule*) u kojem se cijena određuje temeljem svih prodajnih i kupovnih ponuda svih tržišnih sudionika. Od svih pristiglih ponuda za kupnju i za prodaju električne energije formiraju se za svaki sat sljedećeg dana ukupna krivulja ponude (prodaje) i ukupna krivulja potražnje (kupnje). Sjecište ovih dviju krivulja za svaki sat sljedećeg dana definira tržišnu cijenu (engl. *market clearing price*) i ukupnu količinu trgovane električne energije (engl. *market clearing volume*) u satu.

Slika 1 prikazuje primjer određivanja tržišne cijene na burzi APX u Amsterdamu – za dan 23. siječnja 2006. godine tržišna cijena u 16-om satu (od 15:00 do 16:00 sati) iznosila je 81,83 EUR/MWh, a ukupni volumen trgovanja 2 023,5 MWh. U svakom satu svaki kupac za električnu energiju plaća tržišnu cijenu određenu za taj sat, a ista se cijena plaća za električnu energiju prodavatelju. Dakle, u svakom satu svi tržišni sudionici trguju električnom energijom prema istoj jedinstvenoj cijeni.

2.1 Gornja i donja granica cijene na spot tržištu

Na većini spot tržišta gdje se provodi središnja aukcija (dražba) definirane su gornja i donja granica za tržišnu cijenu, odnosno tzv. granične cijene: najveća tržišna cijena (engl. *maximum market price, market price cap*) i najmanja tržišna cijena (engl. *minimum market price, market price floor*). Određivanje njihovog iznosa, posebice najveće tr-

The remainder of the work shortly describes the rule for the determination of the market price prevailing in European countries and the European Energy Exchange, after which an analysis of the actual occurrence of a negative price follows. At the end of the work, events are presented in the Croatian electrical power system which happened at the end of 2008, as well as the impact of the observed situation in western and middle Europe on power flows in the Croatian electrical power system and its direct vicinity.

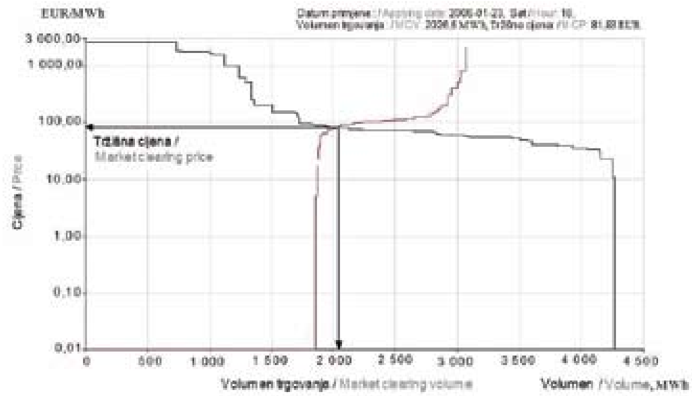
2 SPOT MARKET PRICES CLEARING

Most exchanges organize and undertake the trading on the spot market through a central auction which is held after the expiry of the deadline for submission of bids. Other than this, some exchanges offer the so-called continuous trading method by virtue of which the received bids are put on the market immediately. With such a trading method, when mutually agreeable purchase and sale bids are found, they are immediately realized. In the auction trading method, the market prices are mostly calculated according to the so-called uniform price rule in which the price is set based on all sale and purchase offers of all the market participants. Based on all received bids for purchase and sale of electricity, for each hour of the following day, an overall curve of offer (sale) and an overall curve of demand (purchase) are formed. The intersection of these two curves for each hour of the following day defines the market clearing price and the total market clearing volume in an hour.

Figure 1 shows an example of determination of the market price on the APX exchange in Amsterdam - for the 23rd day of January 2006, market price in the 16th hour (from 15:00 to 16:00 hours) amounted to 81,83 EUR/MWh, and the total market clearing volume was 2 023,5 MWh. In each hour, each buyer pays the market price defined for electricity for that hour, and the same price is paid for electricity to the seller. Therefore, in each hour, all market participants trade in electricity according to the same uniform price.

2.1 Maximum and minimum market prices

On most spot markets where central auction is undertaken, the top and bottom limits of market prices are defined, that is, the so-called cut-off prices: the maximum market price and the minimum market price. Determination of their amount, especially the maximum market price, on an imperfect market such as the electricity market is not at all simple. One should be very care-



Slika 1 — Primjer određivanja cijene na spot tržištu [3]
Figure 1 — Example of spot price calculation [3]

žišne cijene, na nesavršenom tržištu kakvo je tržište električne energije nije nimalo jednostavno. Treba biti vrlo oprezan kako bi se izbjegli negativni, a postigli pozitivni učinci za tržišne sudionike. Zato burze moraju redovito provjeravati jesu li iznosi gornje i donje granice za tržišnu cijenu primjereni te ih po potrebi prilagođavati uvjetima na tržištu električne energije [2].

Ponekad se može dogoditi da sjecište krivulje ukupne ponude i krivulje ukupne potražnje na spot tržištu nije moguće odrediti. Takve se situacije pojavljuju kada na tržištu postoji prevelika ponuda (premala potražnja) ili premala ponuda (prevelika potražnja) električne energije. Prevelika se ponuda obično rješava razmjernim ograničavanjem prodajnih ponuda tako da se krivulje ponude i potražnje presijeku uz najmanju cijenu (slika 2), a prevelika potražnja razmjernim ograničavanjem kupovnih ponuda tako da se krivulje ponude i potražnje presijeku uz najveću cijenu [4]. U oba se slučaja ukupno ograničenje razmjerno raspodjeljuje na tržišne sudionike što znači da će moći prodati odnosno kupiti samo dio električne energije iz svojih ponuda. Neke burze ovakve situacije nastoje riješiti organiziranjem ponovnog prikupljanja novih ponuda tržišnih sudionika i nove središnje aukcije (dražbe). Ako se nakon drugog kruga opet ne može odrediti tržišna cijena, poseže se za razmjernim ograničavanjem [5].

Najmanja tržišna cijena često je 0 EUR/MWh iako nije u skladu sa strukturom troškova proizvodnje električne energije [2], a na nekim je tržištima negativnog iznosa [5] i [6]. Ograničavanje prodajnih ponuda uz cijenu 0 EUR/MWh može prodavateljima izazvati značajne troškove energije uravnoteženja. Zbog toga je prodavateljima odnosno proizvođačima električne energije ponekad ekonomski opravdano da u svojim ponudama za prodaju navode negativne cijene. Oni time pokazuju da su voljni platiti kako bi isporučili svoj proizvod na tržištu te izbjegli moguće dodatne troškove.

ful to avoid negative and achieve positive effects for market participants. The exchanges should therefore check if the amounts of the top and bottom limits are suitable for the market price and adjust them, if necessary, to the conditions on the electricity market [2].

Sometimes it is impossible to define the intersection of the overall offer and overall demand curve on the spot market. Such situations occur when there is excessive offer (insufficient demand) on the market or insufficient offer (excessive demand) of electricity. Excessive offer is usually resolved by proportionate limitation of sales offers so as to intersect the curves of offer and demand along the minimum price (Figure 2), and excessive demand by proportionate limitation of purchase offers so as to intersect the curves of offer and demand along the maximum price [4]. In both cases, the total limitation is proportionately divided onto market participants, which means they will be able to sell or purchase only a part of the electricity from their bids. Some exchanges try to resolve these kinds of situations by organizing a repeated collection of new bids from market participants and new central auctions. If, after a second cycle, the market price cannot be defined again, proportionate limitation is used [5].

The minimum market price is often 0 EUR/MWh although it does not conform to the structure of costs for the production of electricity [2], and in some markets it has a negative amount [5] and [6]. Limitation of sales bids with the price of 0 EUR/MWh may incur significant costs of balance energy for sellers. Therefore, it is sometimes economically justifiable for sellers, that is, producers of electricity to state negative prices in their sales bids. In such way they show that they are willing to pay to dispatch their product onto the market and avoid possible additional costs.

Slika 2 — Ograničavanje ponude uz najmanju cijenu [4]
Figure 2 — Curtailment of sales bids at minimum price [4]

Negativna cijena na tržištu električne energije nije novost niti nepoznanica. Ona već postoji u strukturi nekih kratkoročnih tržišta kao što je tržište energije uravnoteženja [7], spot tržište [6] ili tržište tijekom dana isporuke. Pojavu negativne cijene na spot tržištu može se očekivati u kraćim razdobljima noću, jer je obično od ponoći do ranih jutarnjih sati (od 00:00 do 06:00 sati) potrošnja električne energije najmanja. Smanjenu potrošnju u noćnim satima proizvodnja električne energije može nadmašiti zbog rada postrojenja koja se ne stavljaju izvan pogona zbog njihovih tehničkih karakteristika ili zbog prevelikih troškova njihovog zaustavljanja i ponovnog pokretanja, ili primjerice zbog rada CHP postrojenja koja prvenstveno proizvode toplinu (paru), a električnu energiju kao nusproizvod. Ponekad se negativna cijena može pojaviti kroz dulja vremenska razdoblja i postići velike iznose [6] i [7].

Govoreći općenito o promjeni cijene električne energije tijekom dana, temeljem iskustvenih spoznaja može se reći: ako cijena električne energije približno prati dnevni dijagram opterećenja EES-a, tada nema poremećaja niti posebnih utjecaja koji bi uzrokovali njenu promjenu. Ako se dogodi bilo kakav poremećaj, odnosno ako postoji određeni električki ili neelektrički utjecaj, cijena električne energije reagira većim odstupanjima. Tako, primjerice, veći poremećaj u nekom od susjednih EES-a, poput raspada ili sloma dijela EES-a, može uzrokovati poremećaj cijene na spot tržištu. Takav se primjer dogodio u lipnju 2006. godine kada je u razdoblju vrlo visokih dnevnih temperatura zraka došlo do poremećaja u poljskom EES-u, na što su cijene električne energije na spot tržištu reagirale promptno i višestruko premašile sve dotad postignute iznose.

Negative price on the electricity market is neither new nor unknown. It already exists in the structure of some short-term markets such as the balance energy market [7], the spot market [6] or the intraday market. The occurrence of the negative price on the spot market may be expected in shorter periods of time at night because energy consumption is usually at its lowest from midnight until early morning hours (from 00:00 to 6:00 hours). Production of electricity may overcome reduced consumption in the night hours because of the operation of the facilities which are not put out of operation because of their technical characteristics or excessive costs of stopping and actuating them again, or, for example, because of the operation of the CHP facilities which primarily produce heat (steam), and which produce electricity as a by-product. Sometimes the negative price may occur through longer periods of time and achieve high amounts [6] and [7].

Talking about the alterations of electricity prices during the day, based on experience, it can be said: if the electricity price approximately follows the daily load diagram of the electrical power system, then there are no disruptions or special impacts which might cause its alteration. In case of any disruptions, that is, if there is a certain electrical or non-electrical impact, the electricity price will react with greater derogations. Thus, for example, a significant disruption in one of the neighbouring electrical power systems, such as a blackout or failure of part of the electrical power system, may cause a disruption of the spot market price. Such event occurred in June 2006 when in the period of very high daily air temperatures, there occurred a disruption in the Polish electrical power system which was followed by a prompt reaction of the electricity prices on the spot market which multiply exceeded all the amounts achieved thus far.

3 NEGATIVNA CIJENA ELEKTRIČNE ENERGIJE NA SPOT TRŽIŠTU EEX-A

3.1 Europska burza energije EEX

Europska burza energije EEX stvorena je 2002. godine spajanjem burze električne energije LPX sa sjedištem u Leipzigu (engl. *Leipzig Power Exchange*) i europske burze energije EEX sa sjedištem u Frankfurtu u jedinstvenu europsku burzu energije EEX AG sa sjedištem u Leipzigu (u daljnjem tekstu: EEX). Isprva je poslovanje bilo usredotočeno na trgovanje električnom energijom, a danas obuhvaća prirodni plin, ugljen te tržište emisijama CO_2. U početku se električnom energijom moglo trgovati samo unutar Njemačke, da bi se u travnju 2005. godine područje trgovanja proširilo na regulacijsko područje APG (engl. *Austrian Power Grid*) u Austriji koje zajedno s Njemačkom čini jedno područje trgovanja (engl. *market area*). U prosincu 2006. godine trgovanje na EEX-u je prošireno na područje Švicarske koje čini zasebno područje trgovanja. Danas se na EEX-u nudi organizirano trgovanje:

— električnom energijom na spot tržištu, financijskom tržištu i tržištu tijekom dana isporuke,
— prirodnim plinom na spot tržištu i financijskom tržištu,
— emisijama CO_2 na spot tržištu i financijskom tržištu,
— ugljenom na financijskom tržištu.

U kratkom razdoblju od svog nastanka do danas, u nešto više od 6 godina, EEX se razvila iz lokalne burze električne energije u jednu od najznačajnijih burzi energije u kontinentalnoj Europi. Prema posljednjim podacima s internetskih stranica EEX-a [5] danas na ovoj burzi energije trguje više od 200 tvrtki iz 19 zemalja. Misao vodilja EEX-a je povezivanje tržišta (engl. *connecting markets*) u skladu s kojom EEX neprestano širi paletu energenata i proizvoda koje nudi na svojim tržištima te poslovanje glede zemljopisnog opsega i međunarodne suradnje, čime učvršćuje i širi svoj tržišni položaj.

EEX pruža mogućnost trgovanja električnom energijom za različita vremenska razdoblja u sustavu međusobno povezanih i ovisnih tržišta, u kojem spot tržište ima središnju ulogu. Na spot tržištu EEX-a trguje se tzv. spot ugovorima koji su, s obzirom na vremensko razdoblje isporuke električne energije, ili satni (engl. *hourly contracts*) ili blok ugovori (engl. *block contracts, blocks*) [8].

U satnom se ugovoru trguje električnom energijom konstantnog iznosa snage u jednom satu, dok se u blok ugovoru trguje električnom energijom konstantnog iznosa snage u nekoliko uzastopnih sati. Volumen trgovanja u ugovoru, odnosno količina

3 NEGATIVE PRICE OF ELECTRICITY ON THE EEX SPOT MARKET

3.1 European Energy Exchange (EEX)

The European Energy Exchange EEX was established in 2002 by a merger of the Leipzig Power Exchange and the European Energy Exchange EEX seated in Frankfurt into one single European Energy Exchange EEX AG seated in Leipzig (hereinafter: EEX). The business was first focussed on electricity trade, and now it encompasses natural gas, coal and the CO_2 emissions market. In the beginning, trading in electricity could only be done within Germany; in April 2005 the trading area spread onto the Austrian Power Grid regulation area in Austria which, together with Germany, constitutes a single market area. In December 2006, trading at the EEX was widened onto the Switzerland territory which constitutes a separate market area. Today, EEX offers organized trading:

— in electricity on the spot market, financial market and the intraday market,
— in natural gas on the spot market and the financial market,
— in CO_2 emissions on the spot market and the financial market,
— in coal on the financial market.

In the short period since its establishment up to today, in just over 6 years, the EEX has developed from a local electricity market into one of the most significant energy markets in continental Europe. According to recent data from the EEX web pages [5], more than 200 companies from 19 countries trade at this energy exchange. The EEX's guiding idea of connecting markets is what the EEX continuously follows in order to widen its energy sources and products line up offered on its markets, and to widen its business as regards its geographical radius and international cooperation by which it reinforces and widens its market position.

The EEX offers the possibility of trading in electricity for different periods of time in a system of interrelated and interdependent markets; the spot market has the pivotal role in this. On the EEX's spot market, trading is done in so-called spot contracts which are, as regards the period of time of delivery of electricity, either hourly contracts or block contracts [8].

The hourly contract serves for trading in electricity of constant power amount in one hour, while the block contract serves for trading in electricity of constant power amount in a few consecutive električne energije kojom se trguje određuje se kao umnožak navedene snage i broja sati isporuke. Blok ugovori, ili blok proizvodi, mogu biti standardizirani ili ih u svojim ponudama mogu definirati sami tržišni sudionici. Volumen trgovanja na spot tržištu EEX-a dosegao je oko 15 % ukupne godišnje potrošnje električne energije na području trgovanja EEX-a, a raste iz godine u godinu. Izuzmu li se nordijska burza Nord Pool i burza na Iberijskom poluotoku, ovo je vrlo dobar rezultat u usporedbi s nekim drugim burzama u Europi (primjerice, taj omjer na britanskoj burzi APX UK iznosi oko 2 %, na francuskoj burzi Powernext oko 3 %, na nizozemskoj burzi APX NL oko 12 %) [2].

Na spot tržištu EEX-a gornja granica tržišne cijene bila je i ostala 3 000,0 EUR/MWh, dok je donja granica promijenjena s iznosa 0,0 EUR/MWh na – 3 000,0 EUR/MWh. Pokazalo se da je gornja granica prilično dobro određena i dosada na EEX-u nije zabilježeno ograničavanje ponuda za kupnju električne energije. S druge strane, potreba za promjenom iznosa donje granice i uvođenjem negativne cijene pojavila se zbog nekoliko razloga. U određenim situacijama ponuda na tržištu može biti veća od potražnje uz cijenu 0,0 EUR/MWh. To su, primjerice, situacije u kojima se velika proizvodnja električne energije vjetroelektrana u Njemačkoj ostvaruje u satima smanjene potrošnje.

Takav odnos proizvodnje i potrošnje, odnosno ponude i potražnje može rezultirati razmjernim ograničavanjem ponuda za prodaju električne energije. Na EEX-u to konkretno znači da neke blok ponude neće biti prihvaćene te da će prodavatelji moći prodati samo dio električne energije iz svojih ponuda satnih ugovora. Osim prodavatelja koji nastoje prodati svoje kratkoročne viškove energije putem spot tržišta, razmjerno ograničavanje prodajnih ponuda zahvaća i one tržišne sudionike koji su ranije osigurali svoje fizičke portfelje putem financijskih ugovora, primjerice ročnica (engl. *future contracts, futures*), a sad ih namjeravaju namiriti putem spot tržišta.

EEX kao burza mora jamčiti, u najvećoj mogućoj mjeri, ispunjavanje ugovora sklopljenih posredstvom burze te da međusobno povezani načini trgovanja ponuđeni na burzi pravilno i dobro funkcioniraju. Zbog svega navedenog na EEX-u je odlučeno promijeniti donju granicu cijene na negativan iznos te omogućiti tržišnim sudionicima da u svojim ponudama navode negativne cijene, što u konačnici može rezultirati negativnom cijenom na spot tržištu [9] i [10]. Negativna cijena na EEX-u najprije je uvedena na tržištu tijekom dana isporuke [11], a zatim i na spot tržištu [12] i [13]. Zanimljivo je napomenuti da Nord Pool uskoro namjerava uvesti negativnu cijenu

hours. The volume of trading in the contract, that is, the quantity of electricity which is the subject of the trade, is calculated as a product of the stated power and the number of supply hours. Block contracts, or block products, may be standardized or defined in the bids of the market participants themselves. Trading volume on the EEX's spot market reached about 15 % of the total annual power consumption on the EEX's market area and it increases year after year. If the Nord Pool Nordic exchange and the exchange on the Iberian peninsula are excluded, this is a very good result in comparison to some other exchanges in Europe (for example, that ratio on the British APX UK exchange amounts to about 2 %, on the French Powernext exchange to about 3 %, and on the Netherlands APX NL exchange to about 12 %) [2].

On the EEX's spot market, the top market price limit was, and still is, 3 000,0 EUR/MWh, while the bottom limit was changed from the amount of 0,0 EUR/MWh to – 3 000,0 EUR/MWh. The top limit appears to be well determined and so far limitation of bids for purchase of electricity has not been recorded at the EEX. On the other hand, the need for changing the amount of the bottom limit and for the introduction of the negative price occurred for a few reasons. In certain situations the offer on the market may be greater than the demand at the price 0,0 EUR/MWh. An example of such situation is when high energy production of wind power plants in Germany is realized in the hours of reduced consumption.

Such relation between production and consumption, that is, offer and demand, may result in proportionate limitation of offers for sale of electricity. At the EEX, this particularly means that certain block offers will not be accepted and that the sellers will be able to sell only a part of electricity from their hourly contract offers. Besides the sellers who strive to sell their short-term energy surpluses through the spot market, proportionate limitation of sales bids encompasses also those market participants who ensured their physical portfolios through financial contracts earlier, for example, through future contracts, and now they intend to settle them through the spot market.

As an exchange, the EEX must guarantee, to the maximum extent, fulfillment of contracts concluded by virtue of the exchange and that interrelated trading methods are duly offered on the exchange and that they are functioning well. Due to all of the above, the EEX decided to change the bottom price limit to a negative amount and enable market participants to state negative prices in their offers, which can eventually result in a negative price on the spot market [9] [10]. Negative price at the EEX was first introduced onto the intraday market [11], and then also onto the spot market [12] and [13]. It is interesting to state that Nord Pool intends to in-na spot tržištu električne energije u iznosu od – 200,0 EUR/MWh, posebice zbog učestalih zahtjeva tržišnih sudionika iz Danske gdje je velik udio proizvodnje iz vjetroelektrana.

3.2 Cijena električne energije i volumen trgovanja na spot tržištu EEX-a u prosincu 2008. godine

U radu je razmatrana cijena električne energije i volumen trgovanja na spot tržištu EEX-a tijekom prosinca 2008. godine. Nizom tabličnih i grafičkih prikaza predočene su njihove promjene tijekom mjeseca, tjedna te dana. Podaci korišteni u analizama preuzeti su s internetskih stranica EEX-a [5]. Predočena je međusobna zavisnost cijene i volumena te istaknuto neobično odstupanje cijene u ponedjeljak 22. prosinca 2008. godine u odnosu na isti dan i sate tjedan dana ranije. Radi usporedbe razmatrana su i predočena dva uzastopna tjedna u prosincu 2008. godine. Neobično odstupanje cijene ostvareno je u noćnim satima kada je potrošnja električne energije najmanja. Stoga su u razmatranju posebno izdvojeni i prikazani sati najmanje potrošnje energije tijekom dana: treći (od 02:00 do 03:00), četvrti (od 03:00 do 04:00) i peti sat (od 04:00 do 05:00).

Slikama od 3 do 12 predočene su promjene cijena električne energije u prosincu 2008. godine za različita vremenska razdoblja: od cijelog mjeseca do jednog dana, odnosno odabranih sati. Slike duljih vremenskih razdoblja predočavaju i trend promjene cijene. Na slikama 9, 10, 11 i 12 izdvojene su i prikazane cijene samo za razdoblje smanjene potrošnje električne energije.

Slika 3 prikazuje promjenu satnih cijena električne energije u trećem, četvrtom i petom satu tijekom cijelog prosinca 2008. godine. To su sati najmanjeg opterećenja elektroenergetskog sustava, upravo kada su cijene postigle neobične iznose. Analizirajući cijene za navedene sate tijekom cijelog prosinca uočeno je zadržavanje na manje-više konstantnoj razini tijekom duljeg razdoblja i veliki propad na negativne iznose u ponedjeljak 22. prosinca. Tada su cijene postigle najmanje iznose u povijesti burze EEX. Pad cijena na ovu razinu nije se dogodio iznenada i slučajno.

Slika 4 prikazuje niz satnih cijena tijekom trećeg i četvrtog tjedna prosinca u kojem je prepoznatljiv dnevni uzorak promjene cijene električne energije. Na slici je vidljiv padajući trend cijene. U trećem tjednu cijena se postupno smanjivala prema danima vikenda kada je postigla najmanje iznose. U četvrtom tjednu, osim izrazito velike negativne cijene u jutarnjim satima ponedjeljka, najmanji iznosi cijene postignuti su u vrijeme božićnih blagdana sredinom tjedna, nakon čega se cijena vratila na uobičajenu razinu tijekom vikenda.

troduce the negative price soon onto the electricity spot market in the amount of – 200,0 EUR/MWh, especially due to frequent requests of market participants from Denmark where a large share of the production is covered by the wind power plants.

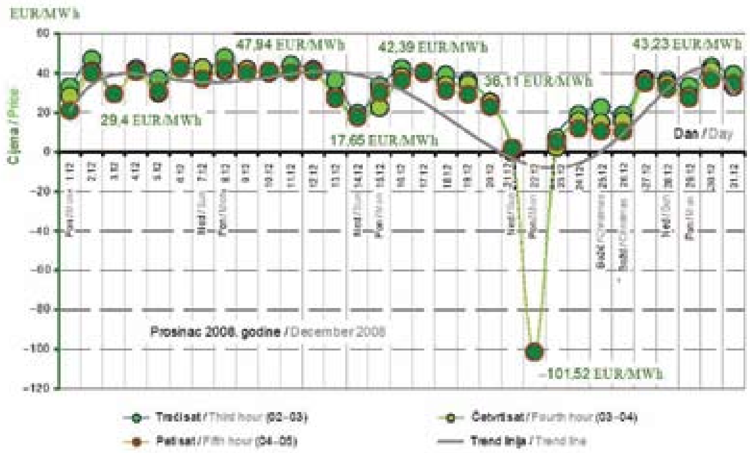
3.2 Electricity price and trading volume on the EEX spot market in December 2008

The work analysed the electricity price and trading volume on the EEX spot market during December 2008. A number of tabular and numerical figures presented their changes during the month, the week and the day. Data used in the analyses were taken over from the EEX's web pages [5]. Interdependency of price and volume is presented and unusual deviation of price on Monday 22 December 2008 is pointed out in relation to the same day and hour a week earlier. For the purpose of comparison, two consecutive weeks in December 2008 are observed. Unusual deviation of price was realized in the night hours when electricity consumption was at its lowest. Therefore, the observation especially singles out and presents the hours of minimum energy consumption during the day: the third (02:00 until 03:00), the fourth (03:00 until 04:00) and the fifth hour (04:00 until 05:00).

Figures 3 to 12 present changes in electricity prices in December 2008 for different periods of time: from a month to one day, that is, selected hours. Figures of longer periods of time present the price change trend as well. Figures 9, 10, 11 and 12 single out and show prices only for the period of reduced energy consumption.

Figure 3 shows a change of hourly prices of electricity in the third, fourth ad fifth hour throughout December 2008. Those are the hours of minimum electrical power system load, and exactly when the prices reached unusual amounts. The analysis of the prices for the above hours during the entire December revealed a lingering on a more or less constant level during a longer period of time and a large fall to negative prices on Monday 22 December. At that time, the prices reached the lowest amounts in the history of the EEX. A fall of the prices to this level happened neither suddenly nor accidentally.

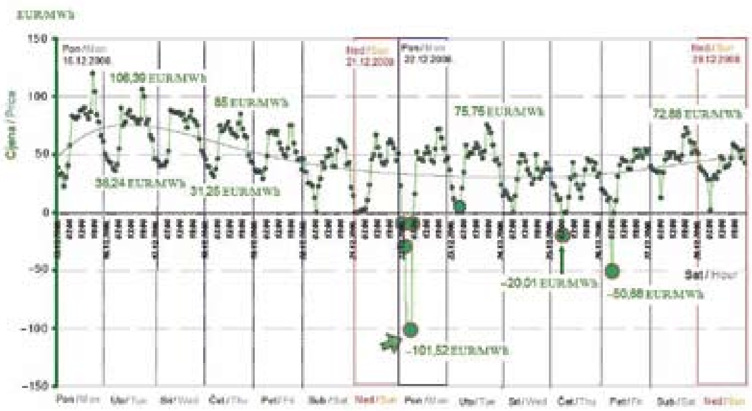
Figure 4 shows a number of hourly prices during the third and fourth week of December in which a daily pattern of electricity price changes is evident. The figure reveals a falling price trend. In the third week, the price was gradually falling towards the weekend days when it reached the lowest amounts. In the fourth week, besides an exceptionally high negative price in the morning hours of Monday, the lowest price amounts were achieved at the time of Christmas holidays in the middle of the week, after which the price returned to the normal level during the weekend.



Slika 3 — Cijene električne energije na EEX-u tijekom noći u vrijeme smanjene potrošnje u prosincu 2008. godine [5]
Figure 3 — Electricity prices on EEX at night during a low consumption period in December 2008 [5]

U istom razdoblju negativne cijene su postignute i za neke standardizirane blok proizvode koji se nude na EEX-u. Cijene postignute za standardizirane blok proizvode u trećem i četvrtom tjednu prosinca prikazane su tablicama 1 i 2, dok su promjene cijena na satnoj razini prikazane tablicama 3 i 4 te slikama od 4 do 8. U tablicama 1 i 2 pored naziva blok proizvoda u zagradama je navedeno i njegovo vremensko razdoblje. U tablicama je namjerno prikazano sedmodnevno razdoblje od petka u jednom tjednu do četvrtka idućeg tjedna radi isticanja neobičnog odstupanja cijena u ponedjeljak 22. prosinca 2008. godine u odnosu na dane neposredno ispred i neposredno nakon. Premda prikazana razdoblja nisu kalendarski tjedni, u radu su nazvani trećim i četvrtim tjednom u prosincu 2008. godine. U četvrtom tjednu (tablica 2) ističe se ponedjeljak 22. prosinca zbog pojave negativnih cijena blok proizvoda Offpeak, Offpeak I te Night. Također, negativna cijena je postignuta za blok proizvod Morning na božićne blagdane: u četvrtak 25. prosinca (– 1,62 EUR/MWh) te u petak 26. prosinca (– 2,54 EUR/MWh). U trećem tjednu prosinca (tablica 1) istaknut je, radi usporedbe, ponedjeljak 15. prosinca. Razlika u cijenama odgovarajućih blok proizvoda uglavnom se kretala od deset do dvadeset posto, a za dva uspoređena ponedjeljka razlika u cijenama je znatno veća.

In the same period, negative prices were reached also for some standardized block products offered at the EEX. Prices achieved for standardized block products in the third and fourth week of December are shown in Tables 1 and 2, while price changes at the hourly level are shown in Tables 3 and 4 and in Figures 4 to 8. In Tables 1 and 2, beside the name of the block products, its period of time is also stated in brackets. The tables intentionally state a seven-day period from Friday in one week until Thursday of the other week for the purpose of accentuating an unusual price deviation on Monday 22 December 2008 in relation to the immediately preceding days and those immediately after. Although the periods shown are not calendar weeks, the work calls them the third and the fourth week in December 2008. In the fourth week (Table 2), Monday 22 December stands out because of the occurrence of negative prices of block products Offpeak, Offpeak I and Night. Moreover, the negative price was also achieved for the block product Morning on Christmas holidays: On Thursday, 25 December (– 1,62 EUR/MWh) and on Friday, 26 December (– 2,54 EUR/MWh). In the third week of December (Table 1), for the purpose of comparison, Monday, 15 December is highlighted. The difference in prices of relevant block products fluctuated mostly from ten to twenty percent, and for the two Mondays compared, the difference in prices was much greater.



Slika 4 — Satne cijene električne energije na EEX-u u trećem i četvrtom tjednu prosinca 2008. godine [5]
Figure 4 — Hourly electricity prices on EEX in the third and the fourth week of December 2008 [5]

Tablica 1 – Cijene blok proizvoda, EUR/MWh na EEX-u u razdoblju od 12.12.2008. do 18.12.2008. [5]
Table 1 – Price of blocks products, EUR/MWh on the EEX from 12 December 2008 to 18 December 2008 [5]

Blok proizvodi / Blocks:		Cijene blok proizvoda / Prices of block products, EUR/MWh						
		Pet / Fri	Sub / Sat	Ned / Sun	Pon / Mon	Uto / Tue	Sri / Wed	Čet / Thu
		12.12.2008.	13.12.2008.	14.12.2008.	15.12.2008.	16.12.2008.	17.12.2008.	18.12.2008.
Offpeak	(20:00–08:00)	–	–	–	–	–	–	–
Offpeak I	(00:00–08:00)	51,77	31,72	15,20	42,45	49,13	49,59	43,62
Offpeak II	(20:00–24:00	58,57	40,48	46,90	63,91	63,84	60,52	50,13
Night	(00:00–06:00)	42,63	32,75	16,72	33,00	41,30	42,53	37,92
Morning	(00:06–10:00	85,34	37,56	17,53	76,15	74,58	78,90	65,78
High noon	(10:00–14:00)	90,85	49,39	42,04	87,27	84,34	85,30	73,41
Afternoon	(14:00–18:00)	87,75	48,60	46,12	93,20	85,72	80,79	73,74
Rush hour	(16:00–20:00)	86,52	57,91	56,44	99,02	90,86	82,30	75,04
Evening	(18:00–24:00)	65,24	46,19	51,16	74,06	72,06	66,81	56,44
Business	(08:00–16:00)	88,55	46,07	36,88	84,69	80,85	83,51	71,02

Tablica 2 – Cijene blok proizvoda, EUR/MWh na EEX-u u razdoblju od 19.12.2008. do 25.12.2008. [5]
Table 2 - Price of block products, EUR/MWh on the EEX from 19 December 2008 to 25 December 2008 [5]

Blok proizvodi / Blocks:		Cijene blok proizvoda / Prices of block products, EUR/MWh						
		Pet / Fri	Sub / Sat	Ned / Sun	Pon / Mon	Uto / Tue	Sri / Wed	Čet / Thu
		19.12.2008.	20.12.2008.	21.12.2008.	22.12.2008.	23.12.2008.	24.12.2008.	25.12.2008.
Offpeak	(20:00–08:00)	–	29,38	17,31	–8,51	29,35	21,83	21,34
Offpeak I	(00:00–08:00)	40,89	23,78	4,21	–35,77	20,17	13,83	12,66
Offpeak II	(20:00–24:00)	45,17	40,58	43,50	46,03	47,71	37,84	38,72
Night	(00:00–06:00)	34,93	27,89	3,43	–59,02	11,38	16,04	20,22
Morning	(06:00–10:00)	64,40	23,91	20,66	40,20	48,22	21,54	–1,62
High noon	(10:00–14:00)	63,08	47,89	55,42	50,82	55,32	44,92	32,19
Afternoon	(14:00–18:00)	57,33	48,68	47,09	53,75	56,80	34,25	23,30
Rush hour	(16:00–20:00)	66,38	59,52	56,73	65,64	67,60	36,57	37,79
Evening	(18:00–24:00)	52,63	47,38	49,49	53,33	55,36	36,38	40,89
Business	(08:00–16:00)	61,41	42,86	46,94	48,05	52,40	38,64	21,85

Tablice 3 i 4 prikazuju satne cijene i volumene trgovanja za dva uspoređena tjedna, pri čemu su istaknuti iznosi za dva uzastopna ponedjeljka. Tijekom noći, odnosno ranih jutarnjih sati (od 00:00 do 06:00 sati) 22. prosinca ostvarene su negativne cijene električne energije na spot tržištu EEX-a, a najveći negativni iznosi ostvareni su u trećem, četvrtom i petom satu (slike 7 i 8). U dnevnom dijagramu opterećenja EES-a, koji ujedno predočava i potrošnju električne energije, vremensko razdoblje od ponoći do 6 sati ujutro je razdoblje najmanje potrošnje električne energije. Pojava veće

Tables 3 and 4 show hourly prices and trading volumes for two compared weeks, whereat amounts are highlighted for two consecutive Mondays. During the night, that is, early morning hours (from 00:00 to 06:00 hours) on 22 December, negative electricity prices were realized on the EEX spot market, and the greatest negative amounts were realized in the third, fourth and fifth hour (Figures 7 and 8). In the daily electrical power system load diagram, which also presents the electricity consumption, the time period between midnight and 6 a.m. is the period of lowest energy consumption.

Tablica 3 – Satne cijene, EUR/MWh i volumeni trgovanja, MWh na spot tržištu EEX-a u razdoblju od 12.12.2008. do 18.12.2008. [5]
Table 3 – Hourly prices, EUR/MWh and trading volumes on the EEX spot market from 12 December 2008 to 18 December 2008 [5]

Sati / Hours	Cijena / Price	Dani / Days						
	Volmen / Volume	Pet / Fri	Sub / Sat	Ned / Sun	Pon / Mon	Uto / Tue	Sri / Wed	Čet / Thu
		12.12.2008.	13.12.2008.	14.12.2008.	15.12.2008.	16.12.2008.	17.12.2008.	18.12.2008.
00–01	EUR/MWh	44,76	41,21	20,15	38,85	46,12	46,17	46,02
	MWh	16 670,60	16 231,50	15 289,40	14 468,70	16 467,20	15 125,50	14 700,10
01–02	EUR/MWh	44,15	36,17	20,79	32,24	43,62	43,91	39,89
	MWh	16 165,10	16 582,20	15 155,90	14 726,60	16 488,20	15 545,30	15 041,10
02–03	EUR/MWh	41,84	36,29	19,47	33,61	42,39	40,08	38,99
	MWh	16 512,70	16 276,30	15 546,20	15 074,60	16 413,70	16 018,70	15 557,50
03–04	EUR/MWh	41,02	28,23	17,68	22,58	38,19	40,59	33,96
	MWh	16 479,90	16 485,10	15 743,10	15 422,60	17 095,40	16 136,30	15 865,60
04–05	EUR/MWh	40,94	26,95	17,65	30,27	36,24	40,55	31,25
	MWh	16 030,70	16 680,80	16 144,70	15 669,50	16 987,40	16 121,30	15 813,00
05–06	EUR/MWh	43,08	27,63	4,56	40,43	41,23	43,90	37,38
	MWh	16 379,00	16 157,70	15 873,20	14 915,40	16 420,00	16 173,70	15 795,00
06–07	EUR/MWh	64,90	27,11	2,06	58,16	55,21	53,08	46,46
	MWh	15 931,10	15 704,90	15 418,00	14 168,10	16 923,50	16 441,10	16 173,70
07–08	EUR/MWh	93,45	30,13	19,25	83,43	90,07	88,40	75,00
	MWh	18 950,50	15 737,10	15 700,50	19 920,90	20 114,70	19 600,60	19 156,00
08–09	EUR/MWh	90,06	41,22	20,17	81,93	75,03	87,30	70,05
	MWh	20 249,40	15 776,70	14 672,00	18 759,30	20 042,80	19 709,50	20 613,80
09–10	EUR/MWh	92,95	51,79	28,65	81,08	77,99	86,82	71,60
	MWh	20 202,20	15 294,00	14 489,10	18 508,20	19 987,40	20 156,40	20 236,60
10–11	EUR/MWh	93,32	53,71	36,68	82,58	85,02	85,93	75,05
	MWh	20 253,80	15 379,30	14 609,90	18 743,20	19 557,90	20 190,40	20 056,40
11–12	EUR/MWh	91,91	52,65	44,81	88,02	88,00	86,40	77,97
	MWh	19 947,60	14 948,20	14 767,20	18 899,30	19 256,80	20 131,30	19 809,80
12–13	EUR/MWh	90,29	48,90	43,50	88,02	82,33	83,70	72,07
	MWh	20 139,40	15 071,70	13 995,30	19 310,50	19 350,20	20 028,30	19 958,40
13–14	EUR/MWh	88,06	42,30	43,18	90,45	82,00	85,17	68,56
	MWh	20 194,20	15 203,40	14 721,30	19 569,60	19 614,50	19 901,70	20 322,00
14–15	EUR/MWh	82,08	38,42	38,97	84,53	79,92	79,80	67,48
	MWh	20 329,70	14 828,00	14 621,20	19 287,20	19 547,10	20 153,50	19 996,70
15–16	EUR/MWh	79,96	39,59	39,09	80,93	76,50	72,94	65,41
	MWh	20 534,70	14 884,80	14 291,00	19 229,90	19 545,50	20 086,30	19 908,40
16–17	EUR/MWh	89,20	47,98	45,92	87,31	80,05	82,52	77,07
	MWh	20 801,40	14 671,00	14 851,10	19 153,20	19 962,30	20 123,50	19 870,90
17–18	EUR/MWh	99,74	68,42	60,49	120,04	106,39	87,91	85,00
	MWh	20 931,20	15 318,80	15 261,20	19 234,60	19 688,00	19 865,80	19 915,40
18–19	EUR/MWh	85,07	64,01	62,85	104,36	100,00	80,07	72,06
	MWh	20 998,80	15 867,70	15 319,00	19 711,20	20 490,20	19 770,50	19 587,00
19–20	EUR/MWh	77,08	51,22	56,51	84,38	77,01	78,71	66,02
	MWh	20 991,90	15 485,30	14 843,60	19 085,80	19 934,20	19 594,70	19 969,30
20–21	EUR/MWh	72,01	46,57	50,03	78,02	80,12	75,05	64,85
	MWh	17 505,80	15 310,50	13 690,00	17 726,40	19 844,30	18 733,70	16 925,30
21–22	EUR/MWh	59,47	39,50	47,95	66,06	66,09	63,69	49,31
	MWh	17 467,80	15 425,50	13 568,50	16 336,00	18 631,30	17 045,30	16 820,60
22–23	EUR/MWh	54,31	39,52	50,71	61,40	63,01	53,53	44,09
	MWh	17 479,60	15 950,90	13 881,20	15 887,60	18 392,50	17 373,00	16 920,60
23-24	EUR/MWh	48,47	36,32	38,91	50,15	46,13	49,82	42,28
	MWh	16 231,80	15 679,80	13 699,80	15 653,50	17 858,00	16 197,30	15 429,50

Tablica 4 – Satne cijene, EUR/MWh i volumeni trgovanja, MWh na spot tržištu EEX-a u razdoblju od 19.12.2008. do 25.12.2008. [5]
Table 4 – Hourly prices, EUR/MWh and trading volumes, MWh on the EEX spot market from 19 December 2008 to 25 December 2008 [5]

Sati / Hours	Cijena / Price Volmen / Volume	Dani / Days						
		Pet / Fri	Sub / Sat	Ned / Sun	Pon / Mon	Uto / Tue	Sri / Wed	Čet / Thu
		19.12.2008.	20.12.2008.	21.12.2008.	22.12.2008.	23.12.2008.	24.12.2008.	25.12.2008.
00–01	EUR/MWh	39,99	46,07	14,68	9,98	21,39	23,93	36,82
	MWh	14 085,50	14 575,50	15 230,30	14 911,50	14 642,40	16 073,50	15 948,20
01–02	EUR/MWh	34,90	35,05	0,08	–29,59	11,44	14,68	24,78
	MWh	14 189,60	15 067,40	14 892,80	15 713,60	14 907,30	15 425,40	16 276,20
02–03	EUR/MWh	36,11	25,14	–0,07	–101,52	6,92	18,88	22,58
	MWh	13 916,90	15 225,80	14 896,70	15 644,70	15 180,80	15 669,20	16 087,50
03–04	EUR/MWh	34,60	25,35	1,08	–101,52	2,33	15,82	14,98
	MWh	13 759,10	15 151,40	15 563,30	15 575,40	15 358,70	15 091,70	15 714,90
04–05	EUR/MWh	29,27	22,93	2,18	–101,50	5,08	11,91	10,62
	MWh	13 905,10	15 358,00	15 488,50	15 664,10	15 466,80	14 879,80	15 576,00
05–06	EUR/MWh	37,70	12,78	2,62	–9,98	21,09	11,03	11,51
	MWh	13 499,60	16 189,90	15 405,00	15 754,80	15 021,70	14 933,70	15 787,60
06–07	EUR/MWh	48,88	0,19	2,66	15,89	34,84	0,06	–20,01
	MWh	13 810,60	16 550,70	16 186,40	16 811,80	15 813,90	15 524,80	15 374,50
07–08	EUR/MWh	68,69	22,76	10,44	52,04	58,29	14,32	–0,01
	MWh	15 625,60	16 606,80	15 725,80	17 181,80	15 529,20	15 963,90	15 482,80
08–09	EUR/MWh	70,02	29,30	23,93	46,14	48,43	28,64	0,47
	MWh	19 041,50	16 502,30	15 082,80	21 679,00	19 246,50	20 715,40	20 365,70
09–10	EUR/MWh	70,01	43,38	45,59	46,71	51,30	43,12	13,09
	MWh	18 561,00	16 895,90	15 406,70	21 869,70	19 412,00	20 593,20	19 744,70
10–11	EUR/MWh	67,58	38,63	49,76	44,11	50,71	49,92	29,34
	MWh	18 269,80	16 350,70	15 750,20	21 161,50	19 077,60	20 228,60	20 535,70
11–12	EUR/MWh	69,84	48,10	66,90	50,72	55,21	48,85	43,19
	MWh	18 328,90	16 549,90	15 899,80	20 413,40	18 590,90	19 499,80	20 658,80
12–13	EUR/MWh	60,07	55,03	56,29	56,49	59,37	44,01	32,12
	MWh	19 223,10	16 780,20	15 540,00	20 936,30	18 883,50	19 770,90	20 670,10
13–14	EUR/MWh	54,82	49,81	48,71	51,94	55,98	36,90	24,09
	MWh	19 131,10	17 166,30	15 487,30	21 548,20	19 218,40	19 462,70	20 511,20
14–15	EUR/MWh	50,19	39,57	43,07	45,07	51,29	33,04	20,01
	MWh	18 811,40	17 042,50	15 938,70	21 465,00	19 718,20	19 407,20	21 190,80
15–16	EUR/MWh	48,71	39,02	41,27	43,25	46,87	24,63	12,46
	MWh	18 949,70	16 822,30	15 560,90	21 206,90	19 425,70	18 653,50	20 756,90
16–17	EUR/MWh	55,41	53,59	43,95	54,98	53,30	29,35	23,00
	MWh	18 652,00	16 653,20	15 320,00	20 208,10	18 751,60	18 440,00	20 931,70
17–18	EUR/MWh	75,02	62,55	60,06	71,68	75,75	49,98	36,84
	MWh	18 149,00	16 372,40	15 781,60	19 772,10	18 898,60	19 820,20	20 250,20
18–19	EUR/MWh	75,04	61,87	62,92	71,78	72,71	37,24	46,50
	MWh	18 881,30	16 212,30	15 270,60	19 712,80	19 150,60	19 849,80	20 252,60
19–20	EUR/MWh	60,05	60,06	59,98	64,10	68,64	29,71	43,95
	MWh	18 769,90	16 177,40	16 200,70	19 725,40	18 977,30	20 029,60	20 475,70
20–21	EUR/MWh	52,15	56,69	55,26	55,39	58,36	34,14	44,21
	MWh	14 248,10	16 632,70	16 326,30	15 069,80	16 248,60	15 623,20	15 509,40
21–22	EUR/MWh	45,06	41,09	44,98	44,75	44,92	36,98	37,13
	MWh	14 247,70	15 997,30	15 686,90	14 630,90	15 292,40	15 885,80	16 209,60
22–23	EUR/MWh	46,49	43,09	50,68	47,14	46,03	42,58	42,32
	MWh	13 936,50	16 005,90	15 579,90	14 292,30	15 868,80	16 205,30	16 600,30
23–24	EUR/MWh	36,96	21,45	23,09	36,82	41,51	37,65	31,20
	MWh	14 167,30	15 059,60	15 598,20	14 280,00	15 810,70	15 717,70	16 379,20

proizvodnje električne energije u odnosu na njenu smanjenu potrošnju najvjerojatnija je u ovom noćnom razdoblju. U skladu s tim ponuda električne energije u tim satima nešto je veća, pa je cijena manja nego u vrijeme dnevne potrošnje. Najveće cijene električne energije ostvarene su u vremenu povećane jutarnje i večernje potrošnje električne energije tj. u satima dnevnog vršnog opterećenja.

Temeljem arhive povijesnih podataka sa spot tržišta EEX-a tablica 5 predočava dane i sate kada su ostvarene negativne cijene električne energi-

The occurence of greater electricity production in relation to its reduced consumption is most probable in this time of night. In accordance with that, the offer of electricity in those hours is somewhat greater and therefore the price is lower than at daytime consumption. The greatest prices of electricity were realized at the time of increased morning and evening electricity consumption, that is, in the hours of the daily peak load.

Based on the historical data archive of the EEX spot market, Table 5 presents the days and the je. U tablicama 4 i 5 zapaža se pojava negativne cijene obično u noćnim, odnosno ranim satima nedjeljnog ili blagdanskog jutra, ali ne tijekom cijele noći, već u jednom, dva ili najviše tri sata. Izuzetak predstavlja ponedjeljak 22. prosinca kada se negativna cijena zadržala tijekom većeg dijela noći.

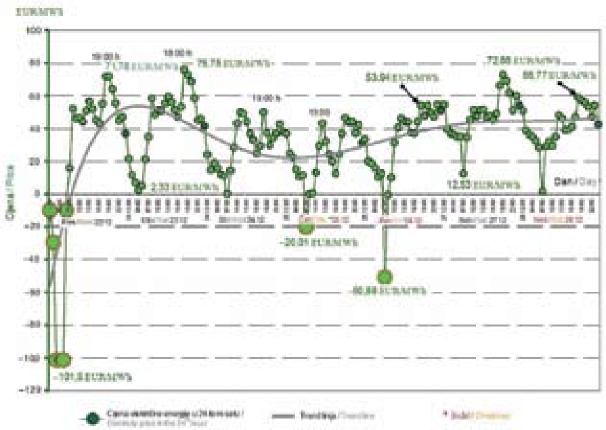
Na slici 5 prikazana je promjena satnih cijena električne energije u četvrtom tjednu prosinca 2008. godine. Posebno se ističu iznosi cijene (71,78 EUR/MWh, 75,75 EUR/MWh i 72,88 EUR/MWh) u razdoblju najveće potrošnje električne energije tijekom dana, što je uobičajeno za razdoblje vršnog opterećenja EES-a (tzv. vršna energija je najskuplja) te negativna cijena u noćnim/jutarnjim satima (–101,52 EUR/MWh). U četvrtom tjednu prosinca su bila dva blagdanska dana: četvrtak 25. prosinca i petak 26. prosinca (božićni blagdani) te nedjelja kao treći neradni dan. Poznato je da su u neradne i blagdanske dane potrošnja električne energije i opterećenje EES-a smanjeni. Posljedično su u te dane cijene i volumeni trgovanja na spot tržištu smanjeni. Osim već spomenute negativne cijene ostvarene u noćnim jutarnjim satima 22. prosinca, negativni iznosi cijene postignuti su i u jutarnjim satima, sedmom i osmom satu, 25. i 26. prosinca. Tijekom cijelog četvrtog tjedna cijene električne energije u ranim jutarnjim satima su male, a u nekim satima su vrlo blizu iznosa 0 EUR/MWh.

hours when negative electricity prices were realized. In Tables 4 and 5 occurrence of the negative price is observed, especially in night, that is, early Monday or Christmas morning hours, but not during the entire night, but in one, two or three hours maximum. En exception is Monday 22 December when the negative price lingered throughout most of the night.

Figure 5 shows a change in hourly prices of electricity in the fourth week of December 2008. Especially distinct are price amounts (71,78 EUR/MWh, 75,75 EUR/MWh and 72,88 EUR/MWh) in the period of highest energy consumption during the day, which is usual for the period of peak loading of the electrical power system (the so-called peak energy is most expensive) and the negative price in night/morning hours (–101,52 EUR/MWh). There were two holidays in the fourth week of December: Thursday, 25 December and Friday, 26 December (Christmas holidays) and Sunday as the third non-working day. It is a well-known fact that on non-working days and holidays energy consumption and electrical power system loading are reduced. This results in reduced prices and volumes of trading on the spot market. Besides the already mentioned negative price realized in early morning hours of 22 December, negative price amounts were also achieved in the morning hours, the seventh and the eighth hour of 25 and 26 December. Throughout the fourth week, the electricity prices in morning hours were small and in some hours very close to the amount of 0 EUR/MWh.

Tablica 5 – Podaci iz baze podataka EEX-a za dane i sate kada je ostvarena negativna cijena električne energije na spot tržištu [5]
Table 5 – Data from the EEX database for days and hours when the negative spot prices occured [5]

Dan / Day	Cijena električne energije / Electricity price, EUR/MWh									
Sati / Hours	00–01	01–02	02–03	03–04	04–05	05–06	06–07	07–08	08–09	09–10
Petak (blagdan) / Friday (holiday) 26.12.2008.	33,45	19,99	18,62	15 86	10,37	12,45	–50,88	–0,61	10,02	31.32
Četvrtak (blagdan) / Thursday (holiday) 25.12.2008.	36,82	24,78	22,58	14,98	10,62	11,51	–20,01	–0,01	0,47	13,09
Ponedjeljak / Monday 22.12.2008.	–9,98	–29,59	–101,52	–101,52	–101,5	–9,98	15,89	52,04	46,14	46,71
Nedjelja / Sunday 21.12.2008.	14,68	0,08	–0,07	1,08	2,18	2,62	2,66	10,44	23,93	45,59
Nedjelja / Sunday 09.11.2008.	49,14	23,82	16,87	7,89	20,14	7,31	–2,16	0,02	9,46	25,59
Nedjelja / Sunday 05.10.2008.	50,79	25,57	1,12	0,05	0,02	–0,02	–1,03	–0,07	44,36	55,10



Slika 5 — Satne cijene električne energije na EEX-u tijekom četvrtog tjedna prosinca 2008. godine [5]

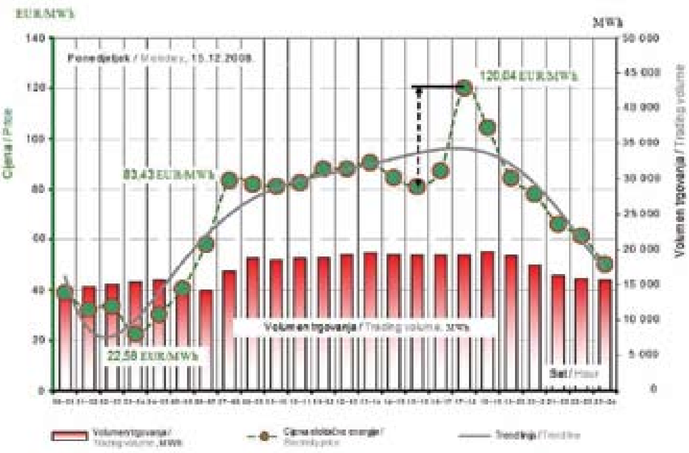
Figure 5 — Hourly electricity prices on EEX in the fourth week of December 2008 [5]

Slike 6 i 7 uspoređuju tijek promjene satnih cijena i volumena trgovanja za dva uzastopna ponedjeljka u prosincu. Slika 6 predočava uobičajenu promjenu satnih cijena u jednom danu koja je karakteristična po smanjenim iznosima tijekom noći i povećanim iznosima tijekom dana. Cijena električne energije najveća je u satima vršnog opterećenja EES-a, a najmanja od ponoći do ranih jutarnjih sati. Slika 7 prikazuje odstupanja od ove uobičajene situacije. Tijekom noći 22. prosinca cijena električne energije u razdoblju od 00:00 do 06:00 sati bila je u svim satima negativna. Najveći negativni iznos od –101,52 EUR/MWh postignut je u trećem i četvrtom satu, a zanemarivo manji od –101,50 EUR/MWh u petom satu. U ostalim satima tog ponedjeljka cijene su u prosjeku osjetno manje nego što su bile prethodnog ponedjeljka – mijenjale su se u opsegu između četrdesetak i sedamdesetak eura po megavatsatu. Porast cijene u satima vršnog opterećenja nije bio tako velik kao prethodnog ponedjeljka – najveća cijena (71,78 EUR/MWh) postignuta je u devetnaestom satu. Ipak, 22. prosinca ni dnevni volumen trgovanja niti volumen trgovanja po satima, posebice u prvih šest sati, nije bio toliko veći koliko bi se moglo očekivati s obzirom na vrlo povoljne cijene. Smanjena potrošnja u tom razdoblju nije mogla iskoristiti obilnu ponudu električne energije bez obzira ne vrlo prihvatljive cijene, odnosno činjenicu da se za kupnju/potrošnju dobivao novac.

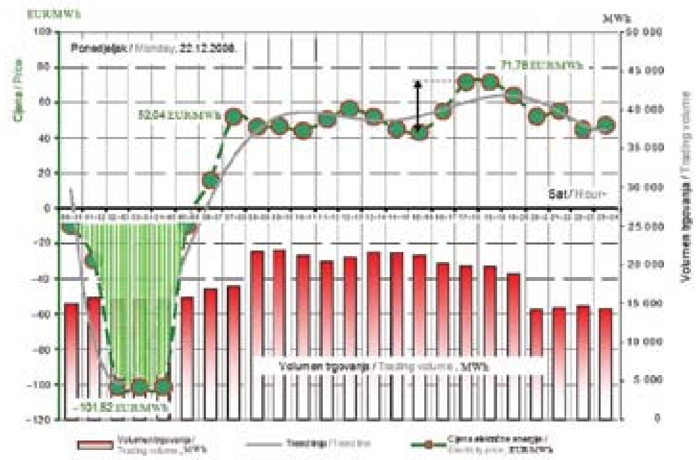
Prikažu li se zajedno na istom grafu satne cijene za dva razmatrana ponedjeljka u prosincu 2008. godine (slika 8) uočavaju se ipak određene sličnosti. Zajedničko je obilježje da su satne cijene električne energije tijekom noći barem dvostruko manje od dnevnih cijena. Zanemare li se za trenutak odstupanja u noćnim satima, trend promjene cijene u oba ponedjeljka je sličan – kao da je translatorno pomaknut po okomici.

Figures 6 and 7 compare the flow of changes of hourly prices and trading volumes for two consecutive Mondays in December. Figure 6 depicts the usual change of hourly prices in one day, which are characteristic for reduced amounts during the night and increased amounts during the day. Electricity price is at its highest in the hours of the electrical power system peak loading, and it is at its lowest from midnight to the early morning hours. Figure 7 shows deviations from this normal situation. During the night of 22 December, electricity price in the period between 00:00 and 06:00 was negative in all the hours. The highest negative amount of –101,52 EUR/MWh was achieved in the third and fourth hour and it is insignificantly lower than –101,50 EUR/MWh in the fifth hour. In the other hours of that Monday, prices were significantly lower than on the previous Monday – they fluctuated in the range between some forty and some seventy euros per megawathour. Increase of price in the peak loading hours was not as high as on the previous Monday – the highest price (71,78 EUR/MWh) was achieved in the nineteenth hour. Nevertheless, on 22 December, neither the daily trading volume nor the hourly trading volume, especially in the first six hours, were as high as could have been expected considering the very advantageous prices. Reduced consumption in that period could not use the abundant offer of electricity regardless of very favourable prices, that is, the fact that money was received for consumption/purchase.

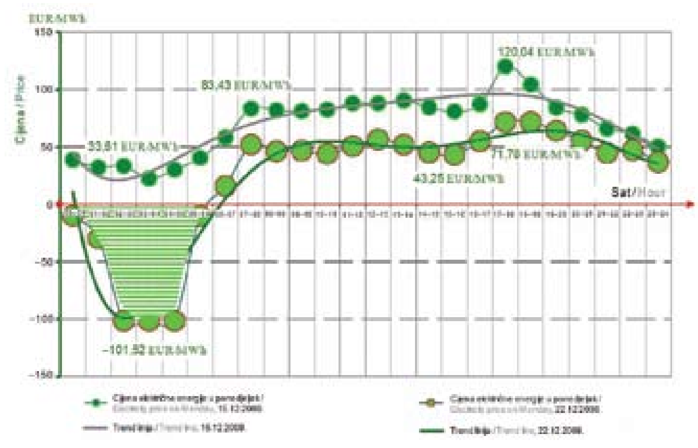
If on the same graph hourly prices are shown for two observed Mondays in December 2008 (Figure 8), certain similarities are nevertheless evident. A common feature is that hourly electricity prices during the night are at least two times as low as the daily prices. If we disregard the deviations in the night hours for a moment, the price change trend for both Mondays is similar- as if moved upon the perpendicular.



Slika 6 — Satne cijene električne energije i volumen trgovanja na EEX-u tijekom dana 15.12.2008. [5]
Figure 6 — Hourly electricity prices and the volume of trading on EEX on 15 December 2008 [5]



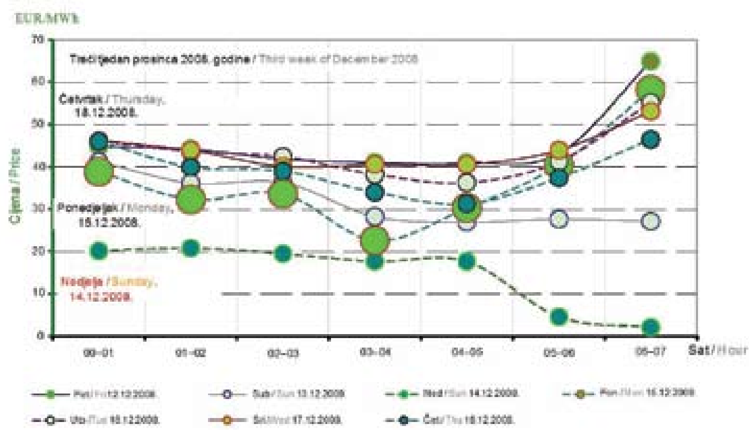
Slika 7 — Satne cijene električne energije i volumen trgovanja na EEX-u tijekom dana 22.12.2008. [5]
Figure 7 — Hourly electricity prices and the volume of trading on EEX on 22 December 2008 [5]



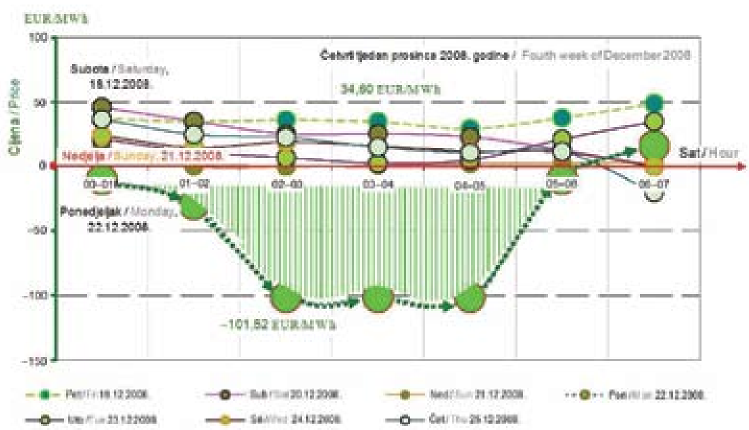
Slika 8 — Usporedba satnih cijena električne energije na EEX-u za dva uzastopna ponedjeljka u prosincu 2008. godine [5]
Figure 8 — Comparison of hourly electricity prices on EEX on two consecutive Mondays in December 2008 [5]

Slike 9 i 10 daju usporedni pregled satnih cijena u prvih sedam sati za sve dane u dva sedmodnevna razdoblja, od petka do idućeg četvrtka, krajem prosinca 2008. godine. Na taj se način može po danima pratiti opseg promjena cijene u određenom satu. U prvom razdoblju (trećem tjednu) primjetan je trend naglog porasta cijene u šestom i sedmom satu za sve radne dane. Slika 10 predočava veliko odstupanje cijena postignutih u ponedjeljak te manju razinu cijene i manje rasipanje za ostale dane u tjednu u odnosu na prethodni tjedan.

Figures 9 and 10 provide a review of hourly prices in the first seven hours for all the days in two seven-day periods, from Friday to next Thursday, at the end of December 2008. In this way, the range of price fluctuations within the particular hour can be followed according to days. In the first period (the third week), a sudden price increasing trend is noticeable in the sixth and seventh hour for all the working days. Figure 10 depicts a great deviation of prices achieved on Monday and a lower price level and lesser dissipation for other days of the week in relation to the previous week.



Slika 9 — Satne cijene električne energije na EEX-u tijekom trećeg tjedna prosinca 2008. godine u satima smanjene potrošnje [5]
Figure 9 — Hourly electricity prices on EEX during a low consumption period in the third week of December 2008 [5]

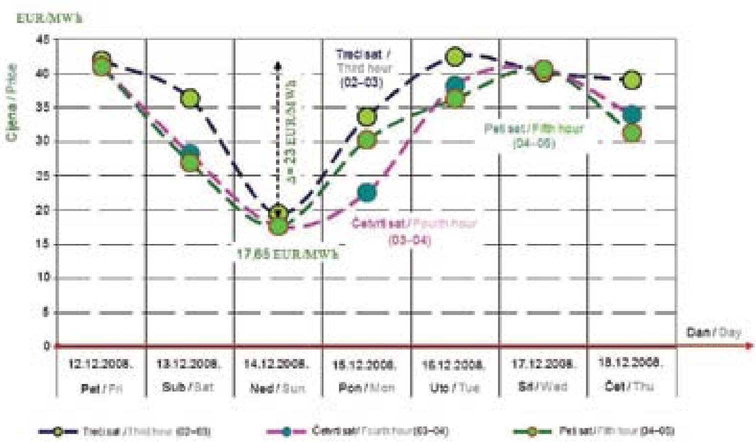


Slika 10 — Satne cijene električne energije na EEX-u tijekom četvrtog tjedna prosinca 2008. godine u satima smanjene potrošnje [5
Figure 10 — Hourly electricity prices during a low consumption period in the forth week of December 2008 [5]

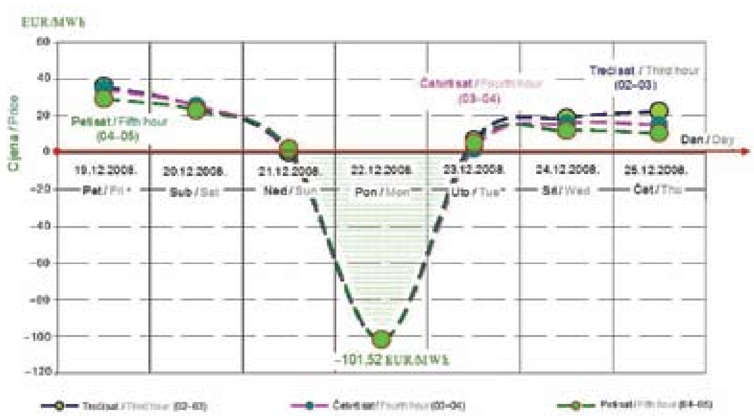
Na slikama 11 i 12 izdvojene su, za sve dane u razmatranim sedmodnevnim razdobljima, cijene samo za treći, četvrti i peti sat u danu, tj. samo za sate kada su potrošnja električne energije i opterećenje EES-a obično najmanjeg iznosa. Gledajući radne dane u tjednu, u ranim jutarnjim satima prvog radnog dana u tjednu zadovoljen je

In Figures 11 and 12, for all the days in the observed seven-day periods, prices are singled out only for the third, fourth and fifth hour of the day, that is, only for those hours when the electricity consumption and the electrical power system loading are usually at their lowest. Looking at the working days of the week, in early morning hours najveći broj uvjeta za postizanje najmanje cijene električne energije. Zaustavljeni tehničko-tehnološki postupci u tim su satima najčešće u režimu grijanja i održavanja stanja. Tek nešto kasnije bit će pokrenuti i tada će početi preuzimanje većih količina električne energije. Na slici 11 je vidljivo da je u trećem tjednu u svim razmatranim satima ostvaren propad cijene od oko 23 EUR/MWh u nedjelju. Cijene u trećem, četvrtom i petom satu u svim danima četvrtog tjedna gotovo da su jednake (slika 12) i manje su nego tjedan dana ranije. Najveća promjena cijena tj. propad veći od 100 EUR/MWh ostvaren je u ponedjeljak kada su cijene postigle praktično isti veliki negativni iznos. Također je vidljivo da su dan ranije (u nedjelju) i dan nakon (u utorak) u svim satima bile vrlo blizu 0 EUR/MWh.

of the first day of the week, most of the conditions for the achievement of the lowest electricity price are met. Technical-technological processes in those hours are non-operative and usually subjected to the heating and state maintenance regime. These will not be actuated until some later time and that is when the taking over of larger amounts of electricity will start. It is evident in Figure 11 that in the third week in all the observed hours a fall of the price of about 23 EUR/MWh was realized on Sunday. Prices in the third, fourth and fifth hour in all the days of the fourth week are almost equal (Figure 12) and lower than a week earlier. The greatest change of prices, that is, a fall greater than 100 EUR/MWh, was realized on Monday when the prices achieved the same high negative amount. It is also evident that a day earlier (on Sunday) and a day later (on Tuesday) these were very close to 0 EUR/MWh throughout the day.



Slika 11 — Cijene električne energije na EEX-u u satima smanjene potrošnje tijekom trećeg tjedna prosinca 2008. godine [5]
Figure 11 — Electricity price on EEX during a low consumption period in the third week of December 2008 [5]



Slika 12 — Cijene električne energije na EEX-u u satima smanjene potrošnje tijekom četvrtog tjedna prosinca 2008. godine [5]
Figure 12 — Electricity prices on EEX during a low consumption period in the fourth week of December 2008 [5]

3.3 Uzroci pojave negativne cijene na EEX-u

Negativna cijena na spot tržištu EEX-a u prosincu 2008. godine rezultat je velikog nerazmjera proizvodnje i potrošnje, odnosno ponude i potražnje električne energije. Nerazmjer može biti posljedica povećane ponude, smanjene potražnje ili i jednog i drugog istodobno. Krajem 2008. godine dogodilo se upravo to da se potražnja smanjila više nego što je uobičajeno, dok je ponuda istodobno bila značajno prevelika. Postavlja se pitanje što je uzrokovalo toliki nerazmjer ponude i potražnje. Zašto je potrošnja električne energije noću bila manja više nego obično te odakle tolika ponuda električne energije na tržištu? Uzroci koji su doveli do pojave negativne cijene različite su prirode, vremena nastanka, jačine i duljine djelovanja.

Prvi od razloga može se potražiti u financijskoj krizi koja je zahvatila gospodarstvo u posljednjem tromjesečju 2008. godine. Krajem godine veliki proizvodni pogoni automobilske industrije smanjivali su proizvodnju, ili čak prestajali s proizvodnjom, te već početkom prosinca poslali radnike na prinudni odmor od mjesec dana. Istodobno su se smanjile cijene metala na svjetskom tržištu, pa su tako, primjerice, proizvođači aluminija i talionice metalnog otpada smanjili svoju proizvodnju. Dakle, gospodarske djelatnosti koje su značajni potrošači električne energije u razmatranom su razdoblju značajno smanjile svoje potrebe za električnom energijom. Ova su se zbivanja vremenski podudarila s početkom godišnjeg odmora koji veliki broj radnika u zapadnoj i središnjoj Europi koristi u vrijeme božićnih blagdana. Upravo je ponedjeljak 22. prosinca bio dan početka dvotjednog godišnjeg odmora. Također, u razmatranom su razdoblju temperature zraka bile umjerene zimske temperature, zbog čega je potrošnja električne energije bila nešto manja od uobičajene za ovo doba godine. Ukupna dnevna potrošnja električne energije za područje trgovanja Njemačka/Austrija na EEX-u u ponedjeljak 22. prosinca bila je desetak posto manja u odnosu na prethodni ponedjeljak, a po satima je bila manja u rasponu od oko 4 % u drugom satu do oko 17 % u sedmom satu [14].

S druge strane, na području središnje Europe ostvarene su obilne padaline unutar tri tjedna krajem 2008. godine (negdje malo ranije, a negdje malo kasnije). One su pridonijele povećanju proizvodnje hidroelektrana te, posljedično, povećanoj ponudi električne energije na burzi po iznimno prihvatljivim cijenama. Nadalje, u ponedjeljak 22. prosinca, otprilike u isto vrijeme, ostvarena je, zbog povoljnog strujanja vjetra, proizvodnja vjetroelektrana u Njemačkoj veća od očekivane. Pritom treba imati na umu da in-

3.3 Causes of occurrence of the negative price at the EEX

The negative price on the EEX spot market in December 2008 is a result of great disproportion between production and consumption, that is, offer and demand of electricity. The disproportion may be a consequence of increased offer, reduced demand or both of these at the same time. At the end of 2008, what happened was exactly that the demand was reduced more than usual, while at the same time, the offer was much too high. The question arises as to what caused such disproportion between offer and demand. Why was the consumption of electricity at night lower than usual and where did such great offer of electricity on the market come from? The causes which led to the occurrence of the negative price are of various natures, times of occurrence, intensity and duration of impact.

The first reason could have originated from the financial crisis which had attacked the economy in the last trimester of the year 2008. At the end of the year, large production plants of the automobile industry were reducing their production, or even stopping it, and, as early as at the beginning of December, sending their workers on one-month forced vacations. Prices of metals on the world market decreased at the same time, and thus, for example, aluminium producers and metal waste melting foundries reduced their production. So, commercial businesses which are significant consumers of electricity greatly reduced their needs for electricity in the observed period. The time when these events happened coincided with the beginning of annual vacations used by many workers in western and middle Europe in the period of Christmas holidays. Monday, 22 December was exactly the day when the two-week annual vacations started. Moreover, in the observed period, air temperatures were moderate winter temperatures, because of which the energy consumption was somewhat lower than the usual for this period of the year. Total daily consumption of electricity for the EEX market area of Germany/Austria on Monday, 22 December was by some ten percent lower in relation to the previous Monday, and, as regards the hours, it was lower in the range of about 4 % in the second hour up to about 17 % in the seventh hour [14].

On the other hand, in the area of middle Europe, abundant rainfall occurred within the three last weeks of the year 2008 (in some places somewhat earlier, in other, somewhat later). These contributed to increased production of hydroelectric power plants and, consequentially, to an increased offer of electricity at exceptionally acceptable prices. Furthermore, on Monday 22 December, at about the same time, wind power plants in Germany realized a production higher than expected due to favourable wind circulation. What should be born in mind thereat is that the installed power of those wind power plants stalirana snaga tih vjetroelektrana nadmašuje 23 GW te da su njihovu proizvedenu energiju tamošnji operatori prijenosnog sustava obvezni preuzeti, zbog uspostavljenog sustava poticanja proizvodnje električne energije iz obnovljivih izvora energije. Dakle, raspolagalo se s viškovima električne energije iz hidroelektrana, čija je energija jeftinija, te iz vjetroelektrana čija se energija u potpunosti preuzima.

U takvoj situaciji neke se termoelektrane moglo staviti u rezervu ili kratkoročno isključiti iz pogona na tjedan dana, čime bi se jednostavnije uravnotežio višak električne energije. Budući da podaci i informacije o tome nisu dostupni, ovdje se pretpostavlja kako je zaključeno da takva mjera potencijalno može imati i negativne učinke po sigurnost sustava. Naime, poznato je da termoelektrane i nuklearne elektrane uz radnu energiju proizvode i dostatnu jalovu energiju čime održavaju stabilnim napone u EES-u i značajno podržavaju stabilnost sustava. Trajan rad termoelektrana i nuklearnih elektrana jamči održavanje naponske i dinamičke stabilnosti povezanih europskih EES-a. One svaki EES čine krutim u odnosu na sve vrste kratkotrajnih prolaznih poremećaja. Može se pretpostaviti da je tijekom noćnih sati, kada su se pojavili viškovi električne energije, jednostavnije i isplativije bilo platiti kupcu nešto više od 100 EUR/MWh i prepustiti energiju, nego dovesti sigurnost sustava u potencijalnu opasnost pojave poremećaja koji bi se teže sanirao. Također, zbog tehničkih karakteristika i troškova zaustavljanja te ponovnog pokretanja proizvodnje u termoelektranama ponekad je ekonomski opravdano ostaviti elektranu u radu i istodobno za to platiti. Dakle, neke termoelektrane vjerojatno nisu smanjivale ili zaustavljale svoju proizvodnju što je također pridonijelo stvaranju viška ponude. Ipak, pretpostavka je da se, kada je i gdje je bilo moguće, smanjivala proizvodnja skupljih termoelektrana (s većim troškovima proizvodnje električne energije) i nadomještavala kupovinom proizvodnje iz hidroelektrana.

Za bolji i cjelovitiji uvid bilo bi zanimljivo vidjeti detalje ponude i potražnje na spot tržištu EEX-a u razmatranom razdoblju, kao i detaljnije podatke o potrošnji i proizvodnji električne energije na području zapadne i središnje Europe u to vrijeme, ali ovi podaci nisu javno dostupni. Usprkos tomu, na temelju svega dosad navedenog može se zaključiti da se u razmatranom razdoblju zbog povećane proizvodnje u hidroelektranama i vjetroelektranama, unatoč vrlo vjerojatnom smanjenju proizvodnje u termoelektranama, raspolagalo značajnim viškovima električne energije koji su ponuđeni na spot tržištu. Povećana ponuda uz istodobno smanjenu potražnju uzrokovala je iz dana u dan padanje cijene elek-

exceeds 23 GW and that the energy they produce has to be taken over by the yonder transmission system operators because of the established system of stimulation of electricity production from renewable sources of energy. Therefore, surpluses of electricity from hydroelectric power plants, which generate cheaper energy, were available as well as those from wind power plants the energy of which is taken over in full.

In such a situation, some thermal power plants could have been put in stand-by mode or turned off for a week which would have made it easier to balance the surplus of electricity. As data and information thereon are not available, the assumption here is that the conclusion was made that such a measure could also possibly negatively affect the system safety. Namely, it is well-known that, together with active power, thermal power plants and nuclear plants produce sufficient reactive power which serves to maintain the stability of the voltages of the electrical power system and significantly support the system stability. Continuous operation of thermal power plants and nuclear plants guarantees the maintenance of voltage and dynamic stability of connected European electrical power systems. These plants make each electrical power system solid against all kinds of short-term transient disruptions. It can be assumed that during the night hours, when electricity surpluses occurred, it was cheaper and more cost-effective to pay the buyer something more than 100 EUR/MWh and let down the energy than to put the system safety at possible risk from occurrence of disruptions which would be more difficult to resolve. Also, due to technical characteristics and costs of stopping and re-actuating the production in thermal power plants, it is sometimes economically justified to leave the power plant in operation and pay for it at the same time. Therefore, some of the power plants probably did not decrease or stop their productions which also contributed to the generation of excessive offer. However, the assumption is that, when and where it was possible, the production of more expensive thermal plants (with higher electricity production costs) decreased and was substituted with purchase of production from the hydroelectric power plants.

For a better and fuller insight, it would be interesting to see offer and demand details on the EEX spot market in the observed period, as well as more detailed data on the consumption and production of electricity in the area of western and middle Europe at that time, but these data are not publicly available. In spite of that, based on everything mentioned so far, it can be concluded that in the observed period, due to an increased production of hydroelectric power plants and wind power plants, in spite of a probable decrease of production in thermal power plants, significant surpluses of electricity were available which were offered on the spot market. Increased offer with trične energije na spot tržištu, što je u konačnici rezultiralo postizanjem velikog negativnog iznosa u noćnim satima 22. prosinca.

4 PRILIKE U HRVATSKOM EES-u KRAJEM 2008. GODINE

4.1 Migracija proizvodnje električne energije u hrvatskom EES-u

Potrebe za električnom energijom u hrvatskom EES-u uglavnom se podmiruju iz tri vrste izvora: proizvodnjom u termoelektranama, proizvodnjom u hidroelektranama te kupovinom električne energije izvan granica Hrvatske. Na godišnjoj razini termoelektrane najvećim dijelom sudjeluju u pokrivanju potrošnje električne energije u Hrvatskoj. Nešto manji udio ostvaruju hidroelektrane, a potom slijede i ostali izvori. Nezanemariv dio ukupnih potreba pokriva se uvozom. Značajno povećanje jednog od načina proizvodnje istodobno rezultira potrebom za smanjenjem proizvodnje drugih skupina izvora. U razdoblju povoljnih hidroloških prilika povećavaju se dotoci, a povećanjem dotoka povećava se količina proizvedene električne energije u hidroelektranama na račun smanjenja proizvodnje u termoelektranama. Omjer proizvodnje električne energije iz termoelektrana i hidroelektrana se neprekidno mijenja na razini sata, dana i mjeseca.

Uobičajeni tokovi snaga u hrvatskom EES-u najčešće imaju smjer od sjevera prema jugu. Krajem 2008. godine, u studenom i prosincu, udio termoelektrana u pokrivanju dnevnih potreba za električnom energijom kretao se u opsegu od 34 % do 55 %dnevne potrošnje električne energije Hrvatske, dok se udio hidroelektrana mijenjao od 18 % do 58 %. U pojedinim danima satni udjeli elektrana u podmirivanju satne potrošnje električne energije mijenjali su se i u većem opsegu od ovdje navedenih iznosa. Povećanjem padalina i dotoka koji su bujičnog karaktera struktura proizvodnje električne energije i smjer tokova energije mijenjao se postupno i neprekidno iz dana u dan. Značajnim povećanjem proizvodnje hidroelektrana smještenih u priobalnom dijelu Hrvatske tok električne energije promijenio je smjer tako da se energija prenosila od juga ka sjeveru. Povećana proizvodnja hidroelektrana potisnula je rad termoelektrana, od kojih su neke prestale s radom. U radu su ostale samo termoelektrane koje sustav čine otpornim na prolazne poremećaje, odnosno koje su važne za stabilnost EES-a. Dakle, zbog obilatih i dugotrajnih povećanja dotoka težište proizvodnje električne energije utemeljeno u Hrvatskoj na velikim termoelektranama u kontinentalnom dijelu zemlje te Istri i Primorju pomaklo se na jug.

a simultaneously reduced demand caused the spot market electricity price to fall day after day, which in the end resulted in the achievement of high negative amounts in the night hours of 22 December.

4 CIRCUMSTANCES IN THE CROATIAN ELECTRICAL POWER SYSTEM AT THE END OF 2008

4.1 Migration of electricity production in the Croatian electrical power system

The needs for electricity of the Croatian electrical power system are mostly settled from three sources: production by thermal power plants, production by hydroelectric power plants and purchase of electricity from outside the borders of Croatia. At the annual level, thermal power plants mostly participate in covering the consumption of electricity in Croatia. A somewhat lesser share is realized by hydroelectric plants and then the other sources follow. A significant part of daily needs is covered by import. A significant increase of one type of production results in the need for a reduction of production of the other source groups. In the period of favourable hydrological circumstances inflows increase, and the increase of inflows increases the quantity of produced electricity in hydroelectric power plants to the detriment of reduction of production in thermal power plants. The ratio of electricity production from thermal power plants and hydroelectric power plants changes constantly on the level of an hour, a day and a month.

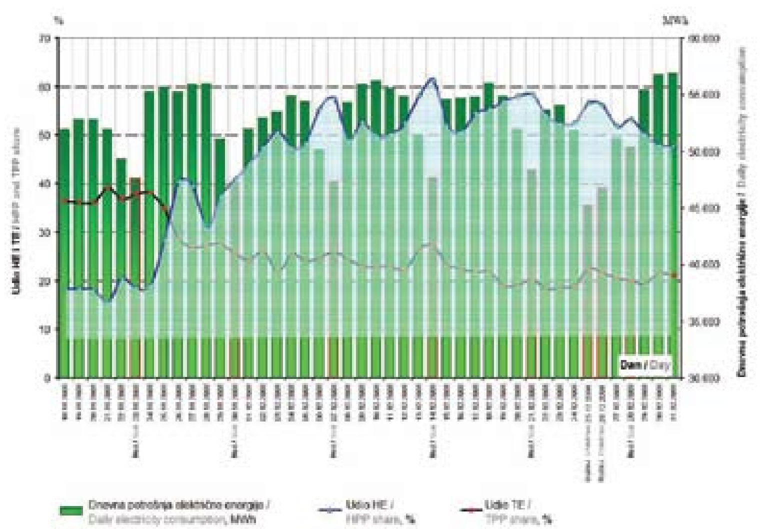
The usual power flows in the Croatian electrical power system are most often directed north to south. At the end of 2008, in November and December, the share of thermal power plants in covering daily needs for electricity fluctuated in the range from 34 % to 55 % of the daily electricity consumption in Croatia, while the share of hydroelectric power plants ranged from 18 % to 58 %. In particular days, hourly shares of power plants in covering hourly electricity consumption changed to the extent even greater than the amounts stated here. Owing to increased rainfall and inflows of torrent character, the structure of electricity production and the direction of power flows changed gradually and constantly day by day. By significantly increasing the production of hydroelectric power plants located in the coastal area of Croatia, the electricity flow changed its direction so that the power was transferred from south to north. Increased production of hydroelectric power plants suppressed the operation of thermal power plants of which some discontinued their operations. Only the thermal power plants which make the system resistant to transient disruptions, that is, those of importance for the stability of the electrical power system re-

Ovom procesu promjene tokova energije pridonijele su svojim povećanim radom i velike hidroelektrane u Bosni i Hercegovini, koje se nalaze u zaleđu hrvatskog EES-a. Veliki dio svoje proizvodnje ove elektrane u pravilu utiskuju u južni dio hrvatskog EES-a, čime pridonose tokovima energije od juga prema sjeveru. Pretpostavka je da se sličan proces promjene strukture proizvodnje električne energije događao u zapadnoj i središnjoj Europi budući da su krajem 2008. godine i tamo ostvarene značajne padaline i povoljni hidrološki uvjeti. Detaljni podaci kojima bi se to potvrdilo nisu javno dostupni.

Slika 13 predočava promjenu strukture proizvodnje električne energije u hrvatskom EES-u u studenom i prosincu 2008. godine – prevladavajuću proizvodnju u termoelektranama zamijenila je proizvodnja u hidroelektranama. Na slici je proizvodnja elektrana prikazana udjelom, % u pokrivanju satne potrošnje električne energije u Hrvatskoj. Vrijedi napomenuti da se zbog obilnih dotoka uz povećanu proizvodnju hidroelektrana istodobno ostvarilo intenzivno punjenje svih hrvatskih akumulacija.

mained operative. Therefore, due to abundant and long-term increases of inflows, the centre of gravity of electricity production established in Croatia on large thermal power plants in the continental part of the country and in Istria and Primorje moved southwards. Increased operation of large hydroelectric power plants in Bosnia and Herzegovina located in the background of the Croatian electrical power system also contributed to this process of changed power flows. These power plants send a large share of their production in the southern part of the Croatian electrical power system, by which they contribute to power flows from south to north. The assumption is that a similar process of change of electricity production structure happened in western and middle Europe because at the end of 2008 significant rainfall and favourable hydrological conditions were realized there as well. Detailed data which would corroborate this are not publicly available.

Figure 13 presents a change of the electricity production structure in the Croatian electrical power system in November and December 2008 – the prevailing production in thermal power plants was substituted by production in hydroelectric power plants. The Figure represents the share of production of power plants of % in covering hourly electricity consumption in Croatia. It is worthwhile to mention that because of abundant flows with increased hydrothermal plants production, intensive filing of all Croatian power plant reservoirs was realized.



Slika 13 — Učešće proizvodnje hidroelektrana i termoelektrana u podmirivanju potrošnje električne energije u Hrvatskoj krajem 2008. godine

Figure 13 — Participation of hydropower plants and thermal power plants in daily consumption of Croatia at the end of year 2008

Ista su događanja podrobnije predočena primjerima koji predstavljaju hidrološki različita zimska

The same events are presented in more detail by virtue of examples which represent hydrologically razdoblja. Za primjere su odabrani dan 23. studenog 2008. godine koji predstavlja uobičajeno zimsko relativno sušno razdoblje, te dan 14. prosinca 2008. godine kao primjer izrazito povoljne hidrologije kad je proizvodnja hidroelektrana značajno povećana. Za razdoblje sredine mjeseca studenog može se reći da je uobičajeno razdoblje bez velikih dotoka. Nakon 23. studenog 2008. godine do kraja godine bilo je hidrološki povoljno zimsko razdoblje s obilnim dotocima vode u trajnom porastu, što već dugo nije zabilježeno. U zimskom relativno sušnom razdoblju većinu potrošnje podmirivala je proizvodnja u termoelektranama (na dnevnoj razini oko 55 %), manji dio podmirivao se proizvodnjom u hidroelektranama (na dnevnoj razini oko 21 %), dok je preostala potrošnja pokrivena vrlo malim udjelom ostalih proizvodnih postrojenja i uglavnom uvozom električne energije. U razdoblju povoljne hidrologije struktura proizvodnje u hrvatskom EES-u bila je bitno različita, odnosno upravo obrnuta. Većina se potrošnje podmirivala iz hidroelektrana (na dnevnoj razini oko 58 %), a manji dio iz termoelektrana (na dnevnoj razini oko 25 %). Kao i u prethodnom primjeru, preostala potrošnja pokrivena je uvozom električne energije i vrlo mali dio proizvodnjom u ostalim proizvodnim postrojenjima. Iako se tijekom prosinca cijena električne energije u Europi smanjivala, veći uvoz električne energije u Hrvatsku za potrebe domaće potrošnje nije ostvaren zbog velike količine raspoložive energije u hidroelektranama hrvatskog EES-a.

Slike 14 i 15 su prikazi trenutačne bilance snaga dobiveni iz programa Dispečerska analiza mreže (DAM) u kojem se podaci i grafički prikazi osvježavaju s vrlo velikom učestalošću. Budući da je relativno teško uhvatiti isti trenutak u različitim danima, prikazane su prilike u EES-u u različitim trenucima unutar istog sata. U ovom radu to nije predstavljalo poteškoću, jer su razmatrani iznosi tržišne cijene i volumena trgovanja na razini sata. Slikama su prikazane bilance tokova snaga na svim granicama hrvatskog EES-a te tokovi snaga na nekim značajnijim dalekovodima 400 kV i 200 kV koji predstavljaju važne povezne pravce u regiji jugoistočne Europe. Obje slike prikazuju bilance snaga tijekom šestog sata ujutro u nedjelju (23. studenog 2008. i 14. prosinca 2008. godine). Opterećenje je bilo približno istog iznosa (oko 1 510 MWh/h i 1 513 MWh/h), ali se proizvodnja u hidroelektranama i termoelektranama bitno razlikovala (ukupno 752 MWh i 1 222 MWh). Usporede li se bilance po granicama može se primijetiti povećanje uvoza iz Mađarske (oko 150 MW) i Bosne i Hercegovine (oko 90 MW) te značajno povećanje izvoza u Sloveniju (oko 630 MW). Slični su iznosi ostvareni tijekom cijele noći razmatranog vlažnog zimskog dana. Slične prilike u prijenosnoj

different winter periods. The following are chosen as examples: 23 November 2008, which represents the usual, relatively dry, winter season, and 14 December 2008 as an example of extremely favourable hydrology when the production of hydroelectric power plants increased significantly. For the period of the middle of November it can be said that it is the usual period without great inflows. The period between 23 November 2008 and the end of the year was a hydrologically favourable winter period with abundant and constantly increasing water inflows such as had not been recorded in a long time. In the relatively dry winter season, most of the consumption was settled by production of thermal power plants (at a daily level of about 55 %), a smaller share was settled by production of hydroelectric power plants (at a daily level of about 21 %), while the remaining consumption was covered by a very low share of the other production facilities and mainly by import of electricity. In the period of favourable hydrology, the production structure in the Croatian electrical power system was significantly different, that is, exactly the opposite. Most of the consumption was settled from hydroelectric plants (at a daily basis of about 58 %), and a smaller share from thermal power plants (at a daily basis of about 25 %). Just as in the previous example, the remaining consumption was covered by import of electricity and a very small share by production in the other production plants. Although during December the electricity price in Europe was reduced, a greater import of electricity into Croatia, for the needs of domestic consumption, was not realized due to large amounts of available power in the hydroelectric power plants of the Croatian electrical power system.

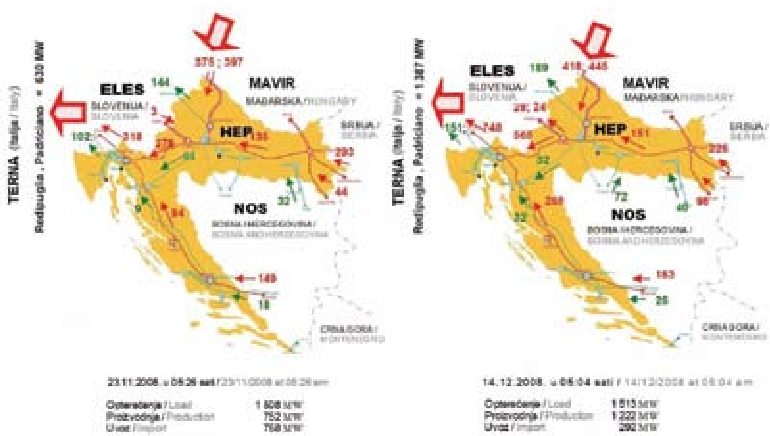
Figures 14 and 15 are presentations of the current power balances obtained by the Dispatcher Network Analysis (DAM) program in which data and graphic figures are updated at a very frequent rate. As the same moment in different days can hardly be captured, circumstances in the electrical power system in different moments of the same hour are shown. This did not create a problem in this work because market price amounts and trade volumes were considered at the level of an hour. The figures show power flow balances at all the borders of the electrical power system, and power flows on certain significant transmission lines 400 kV and 200 kV which represent important connection routes in the south-eastern Europe region. Both figures show power balances during the sixth hour of Sunday morning (23 November 2008 and 14 December 2008). Load was approximately of the same amount (about 1 510 MWh/h and about 1 513 MWh/h), but the production at hydroelectric power plants and thermal power plants varied significantly (total of 752 MWh and about 1 222 MWh). If balances at the borders are compared, an increase of import from Hungary is evident (about 150 MW) and from Bosnia and Herzegovina (about 90 MW), as well as significant increase of export into Slovenia (about 630 MW).

mreži 400 kV i 220 kV hrvatskog EES-a za odabrana hidrološki različita razdoblja prikazane su slikom 16.

Similar amounts were realized throughout the night of the observed winter day. Similar circumstances in the 400 kV and 220 kV transmission network and in the Croatian electrical power system for the chosen, hydrologically different, periods are shown in Figure 16.

Slika 14 — Tokovi snaga u zimskom sušnom razdoblju (studeni 2008. godine) [15]
Figure 14 — Power flows during dry winter period (November 2008) [15]

Slika 15 — Tokovi snaga u razdoblju povećanih dotoka zimi (prosinac 2008. godine) [15]
Figure 15 — Power flows during favourable hydrology in winter period (December 2008) [15]



Slika 16 — Tokovi snaga u prijenosnoj mreži 400 kV i 220 kV hrvatskog EES-a u dva zimska hidrološki različita razdoblja [15], [16]
Figure 16 — Power flows in 400 kV and 220 kV transmission network of Croatian power system for different hydrology in winter period [15], [16]

4.2 Promjena tokova snaga u hrvatskom EES-u

Operator prijenosnog sustava po svojoj osnovnoj zadaći nema dodira s cijenama električne energije na spot tržištu. Trgovački tokovi električne energije u pravilu se ne podudaraju sa stvarnim fizičkim tokovima električne energije, ali promjene u trgovanju električnom energijom mogu rezultirati bitnim promjenama fizičkih tokova snaga. Stoga operator prijenosnog sustava, odnosno voditelj sustava može zamijetiti značajnije promjene cijena posredno kroz neobične fizičke tokove snaga. Takav je učinak povremeno zamijećen u hrvatskom EES-u tijekom tri tjedna prosinca 2008. godine, kada je zamjetna promjena tokova snaga bila vidljiva noću od 00:00 do 06:00 sati.

Promjenu tokova snaga u EES-u prvenstveno uzrokuje promjena proizvodnje, ali i značajna razmjena električne energije sa susjednim EES-ima. Kao što je u radu već navedeno, u prosincu 2008. godine cijena električne energije bila je višestruko povoljnija nego cijena električne energije koju bi proizvele domaće termoelektrane u nekim europskim zemljama. Zato su tranziti električne energije u Europi promijenili iznos i smjer tako da je energija iz dotocima bogatih regija, gdje su smještene velike hidroelektrane, imala smjer prema regijama s velikom potrošnjom električne energije.

Krajem 2008. godine u hrvatskom EES-u zapažene su dvije značajne promjene tokova snaga. Prvo se zapažanje odnosi na promjenu iznosa i smjera tokova snaga u hrvatskom EES-u uzrokovanu povećanjem i preraspodjelom proizvodnje. Zbog trajno povećane proizvodnje u najvećim hidroelektranama na jugu hrvatskog EES-a te u Bosni i Hercegovini kao njegovom energetskom zaleđu, zbog smanjenog uvoza električne energije za potrebe domaće potrošnje te prestanka rada nekih termoelektrana, uobičajeni smjer toka energije od sjevera prema jugu promijenjen je u smjer od juga prema sjeveru. Drugo se zapažanje odnosi na promjene tranzitiranja električne energije preko hrvatskog EES-a. Tokovi snaga iz Mađarske preko hrvatskog EES-a u smjeru Italije su povećani osobito u noćnim satima. Do ove pojave došlo je zbog malih cijena električne energije u središnjoj i zapadnoj Europi. Električna energija ponuđena na tržištu po povoljnim cijenama kupljena je i uvezena u Italiju kao zamjena za skuplju domaću proizvodnju u termoelektranama. Uvezena energija također je korištena za rad crpnih elektrana čija instalirana snaga u Italiji prelazi 7 600 MW. Na taj se način jeftina električna energija pohranjivala u akumulacijama za kasniju uporabu kada se, primjerice, tržišne cijene povećaju.

4.2 Change of power flows in the Croatian electrical power system

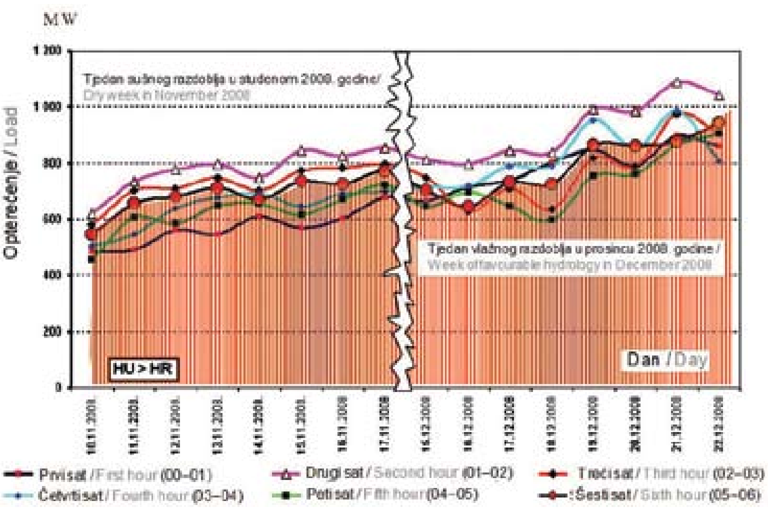
The basic task of the transmission system operator does not put him in contact with electricity prices on the spot market. Electricity trade routes generally do not coincide with actual physical electricity flows, but changes in electricity trading may result in significant changes of physical power flows. Therefore, the transmission system operator, that is, the system manager, can notice significant price variations indirectly through unusual physical power flows. Such effect was occasionally noticed in the Croatian electrical power system during the three weeks of December 2008 when a noticeable change in power flows was evident at night from 00:00 to 06:00.

The change in power flows of the electrical power system is primarily caused by a change of production, but also by a significant exchange of electricity with the neighbouring electrical power systems. As has already been mentioned in the work, in December 2008, the electricity price was several times more favourable than the price of electricity which would have been produced by domestic thermal power plants in certain European countries. Therefore, the electricity transits in Europe changed their directions and amounts so that the energy from the inflow-rich regions, where large hydroelectric power plants are located, was directed towards the regions with high electricity consumption.

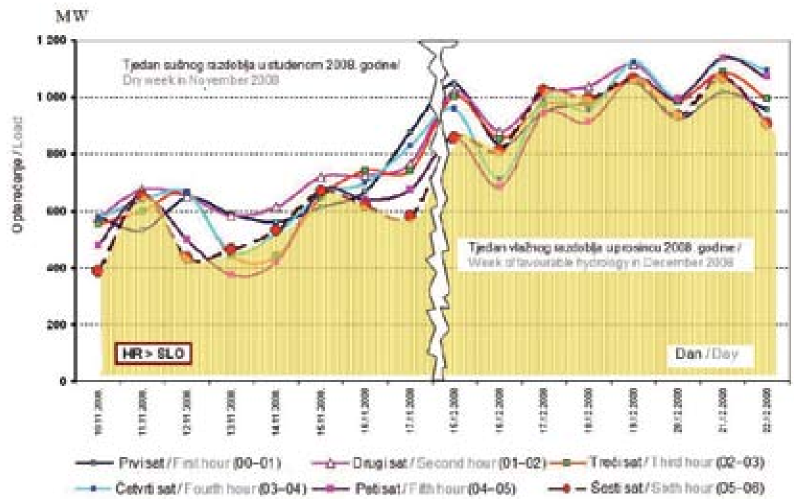
At the end of 2008, two significant power flow changes were noticed in the Croatian electrical power system. The first observation relates to the change of power flow amounts and directions in the Croatian electrical power system caused by increase and redistribution of production. Due to a permanent increase of production in the largest hydroelectric power plants in the south of the Croatian electrical power system and in Bosnia and Herzegovina as its energy background, due to a reduced import of electricity for the needs of domestic production and the termination of operation of certain thermal power plants, the usual direction of the power flow from north to south was changed to the direction from south to north. The second observation relates to changes in transits of electricity through the Croatian electrical power system. Power flows from Hungary through the Croatian electrical power system towards Italy were increased, especially in night hours. This occurrence was caused by low electricity prices in middle and western Europe. The electricity offered on the market at favourable prices was bought and imported into Italy as substitution for the more expensive domestic production in thermal power plants. The imported energy was also used for the operation of pumping power plants whose installed power in Italy exceeds 7 600 MW. In such a way, cheap electricity was stored in reservoirs for later use, when, for example, market prices increase.

Dakle, u razmatranom se razdoblju dogodilo značajno povećanje proizvodnje električne energije na jugu hrvatskog EES-a koja je odlazila u pravcu sjevera i najvećih potrošača te povećani ulaz električne energije iz smjera Bosne i Hercegovine i Mađarske u Hrvatsku. Najveći dio ove energije, odnosno tokova snaga, uočen je na granici Hrvatske i Slovenije te dalje na granici Slovenije i Italije. Slike 17, 18 i 19 prikazuju opterećenja dalekovoda na granicama Mađarske i Hrvatske, Hrvatske i Slovenije te Slovenije i Italije u noćnim satima (od 00:00 do 06:00 sati). Ovdje su u istom grafičkom prikazu predočena opterećenja za sušno razdoblje sredinom studenog 2008. godine te za vlažno razdoblje od 15. do 22. prosinca 2008. godine. Grafički prikazi stvoreni su temeljem podataka iz sustava Vulcanus [16]. Slike predočavaju trend porasta prekograničnih tokova u smjeru Italije koji se podudaraju s pojavom male cijene električne energije na spot tržištu koja je razmatrana u ovom radu. Dio tokova snaga na slovensko-talijanskoj granici zatvorio se kroz mađarski, hrvatski i slovenski EES, dok se dio zatvorio kroz austrijski i slovenski EES. Na sve tri slike površinom ispod krivulje predstavljen je prekogranični tok električne energije u šestom satu (od 05:00 do 06:00 sati).

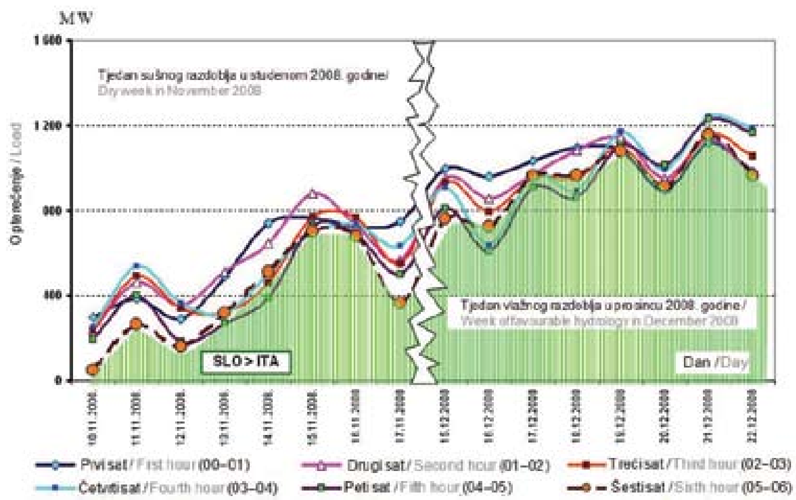
So, in the observed period, a significant increase of electricity production occurred in the south of the Croatian electrical power system which went towards north and the largest users, and an increased input of electricity from Bosnia and Herzegovina and Hungary into Croatia. The largest share of this power, that is, of power flows, was noticed at the border between Croatia and Slovenia and farther at the border of Slovenia and Italy. Figures 17, 18 and 19 show transmission lines loads at the borders between Hungary and Croatia, Croatia and Slovenia, Slovenia and Italy in the night hours (from 00:00 to 06:00). Here, in the same graphic presentation, loads are shown for the dry period at the middle of November 2008, and for the wet period from 15 to 22 December 2008. Graphic presentations are created according to the data from the Vulcanus system [16]. The figures depict the growth trend of cross-border flows towards Italy which coincide with the occurrence of low electricity prices on the spot market which has been elaborated in this work. Part of the power flows at the Slovenian-Italian border was closed through the Hungarian, Croatian and Slovenian electrical power system, while a part was closed through the Austrian and Slovenian electrical power system. In all the three figures, the surface under the curve shows the cross-border flow of electricity in the sixth hour (from 05:00 to 06:00).



Slika 17 — Prekogranični tokovi snaga iz Mađarske u Hrvatsku tijekom noći u sušnom i vlažnom zimskom razdoblju 2008. godine [16]
Figure 17 — Cross-border power flows from Hungary to Croatia during night for dry and wet winter period in year 2008 [16]



Slika 18 — Prekogranični tokovi snaga iz Hrvatske u Sloveniju tijekom noći u sušnom i vlažnom zimskom razdoblju 2008. godine [16]
Figure 18 — Cross-border power flows from Croatia to Slovenia during night for dry and wet winter period in year 2008 [16]



Slika 19 — Prekogranični tokovi električne energije iz Sloveniju u Italiju tijekom noći u sušnom i vlažnom zimskom razdoblju 2008. godine [16]
Figure 19 — Cross-border power flows from Slovenia to Italy during night for dry and wet winter period in year 2008 [16]

5 ZAKLJUČAK

Negativna cijena na spot tržištu EEX-a rezultat je zajedničkog djelovanja više čimbenika koji su se istodobno dogodili krajem 2008. godine. Kraj godine obično nije razdoblje pojačavanja gospodarske djelatnosti, početka novog proizvodnog ciklusa i sl., već je to razdoblje privođenja poslova kraju te ulaska u blagdansko raspoloženje i vrijeme odmora. Krajem godine u vrijeme božićnih blagdana veći broj radnika obično koristi jedan do dva tjedna godišnjeg odmora. Uz ove uobičajene uvjete i događaje karakteristične za kraj svake godine, kraj 2008. godine obilježile su sljedeće specifičnosti:

5 CONCLUSION

The negative price on the EEX spot market is a result of joint effect of several factors which occurred simultaneously at the end of 2008. The end of the year usually is not the period when economic activity increases, a new production cycle starts, etc. but it is a period when work is being brought to an end and when the holiday spirit starts to set in and people rest. At the end of the year, at the time of Christmas holidays, a large number of workers usually use one to two weeks of their annual vacations. Besides these usual conditions and events typical for the end of each year, the end of 2008 was also marked by the following specificities:

— nepovoljna opća gospodarska situacija i smanjivanje proizvodnje u velikom broju gospodarskih djelatnosti koje inače troše značajne količine električne energije za svoj rad, kao što su automobilska industrija ili proizvodnja aluminija,
— zaustavljanje proizvodnje u prosincu 2008. godine u automobilskoj industriji na mjesec dana i prinudan odmor za više od 250 000 radnika samo u Njemačkoj,
— umjereno i blago zimsko razdoblje s temperaturama zraka koje su neuobičajene za ovo doba godine,
— povoljni hidrološki uvjeti i povećani dotoci po iznosu i trajanju neuobičajeni u ovom godišnjem razdoblju,
— povoljno strujanje vjetra i povećana proizvodnja električne energije iz vjetroelektrana u noćnim satima.

Sve zajedno dovelo je do istodobnog smanjenja potrošnje i povećanja proizvodnje električne energije, što je pak uzrokovalo višestruko veću ponudu od potražnje i rezultiralo negativnom cijenom na spot tržištu EEX-a. Negativna cijena postignuta je noću kada je potrošnja električne energije uobičajeno najmanja. Međutim, temeljem pojave analizirane u ovom radu ne može se pojednostavljeno zaključiti hoće li se slične situacije ubuduće događati na spot tržištu električne energije. Vrlo vjerojatno neće svaki put uz povoljne hidrološke uvjete i pojačano povoljno strujanje vjetra tržišna cijena električne energije na burzi postizati dugotrajno negativne iznose. Također, preuranjeno je davati ocjene radi li se ovdje o rijetkoj pojavi na spot tržištu EEX-a budući da je uporaba negativne cijene na EEX-u uvedena relativno nedavno (od 19. prosinca 2007. godine na tržištu tijekom dana isporuke te od 1. rujna 2008. godine na spot tržištu). Čini se kako se odluka EEX-a o uvođenju negativne cijene brzo pokazala korisnom i opravdanom.

Zbog dobre povezanosti europskih EES-a stanje u zapadnoj i središnjoj Europi krajem 2008. godine odrazilo se na fizičke tokove snaga u hrvatskom EES-u i njegovom okruženju. Zabilježeno je povećanje razmjene električne energije noću preko hrvatskog EES-a, bez većih poremećaja i posljedica na njegov rad i sigurnost opskrbe krajnjih potrošača.

— unfavourable general economic situation and reduction of production in a large share of economic activities which normally use significant amounts of electricity for own operation, such as automobile industry and aluminium production,
— stopping the production in December 2008 in the automobile industry for a month and forced vacation for more than 250 000 workers in Germany only,
— moderate and mild winter period with air temperatures which are usually not realized in that time of year,
— favourable hydrological conditions and increased inflows, as regards their rate and duration, unusual for that time of the year,
— favourable wind circulation and increased electricity production from the wind power plants in the night hours,

All of this together caused a simultaneous reduction of consumption and increase of production of electricity, which in turn caused the offer to become several times higher than demand and resulted in a negative price on the EEX spot market. The negative price was achieved at night when electricity consumption is usually reduced. However, based on the occurrence analysed in this work, it cannot be simply concluded whether or not similar situations will happen in the future on the electricity spot market. It is quite probable that, with favourable hydrological conditions and increased favourable wind circulation, the electricity market price will not achieve lasting negative amounts each time. Moreover, it is too early to assess whether this occurrence is rare on the EEX spot market because the use of the negative price on the EEX was introduced relatively recently (on 19 December 2007 on the intraday market and as of 1 September 2008 on the spot market). It seems that the EEX decision on the introduction of the negative price turned out as useful and justified soon.

Due to good connection between the European electrical power systems, the situation in western and middle Europe at the end of 2008 impacted the power flows in the Croatian electrical power system and its surroundings. An increase of exchange of electricity at night through the Croatian electrical power system was recorded, without significant disruptions and consequences to its operation and security of supply of the end users.

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ANALIZA VELIKOG KVARA U TRAFOSTANICI NA OTOKU KRETI
THE STUDY OF A MAJOR 2008 SUBSTATION INCIDENT IN THE EPS OF CRETE

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Predmet članka je veliki kvar u elektroenergetskom sustavu Krete koji je za posljedicu imao veliku štetu na TS Iraklio 3 (150/15 kV). Problem je počeo zbog kvara na srednjem naponu u transformatorskoj stanici. Kvar nije uklonjen zbog istodobnog uništenja zaštite i kontrolnih strujnih krugova što je rezultiralo velikim strujama kratkog spoja tijekom 16 minuta, požarima na opremi i velikom štetom na visokom naponu, srednjem naponu kao i uređajima istosmjerne struje u transformatorskoj stanici, uz znatnu redukciju opterećenja. Članak počinje procjenom stanja elektroenergetskog sustava u trenutku nastanka kvara. Potom slijedi opis slijeda događaja tog kvara. Podrobno se opisuju proizašle mjere koje uključuju ponovnu uspostavu normalne opskrbe energijom, djelomičan povratak u pogon kao i konačan dovršetak popravaka na objektu transformatorske stanice. Predstavljena je analiza kvara. Doneseni su zaključci od praktične važnosti kao i preporuke u odnosu na poboljšanja u hardverskom i zaštitnom sustavu i dostupnoj tehničkoj potpori, koje mogu biti presudne za izbjegavanje i/ili ograničavanje štete kod budućih kvarova.

A major incident in the Electric Power System (EPS) of Crete resulting in extensive damages in the SS Iraklio 3, 150/15 kV is studied. The accident originated from a medium voltage fault at the substation. This fault was not cleared due to the coincident destruction of the protection and control circuits resulting in large short-circuit currents for 16 minutes, fires of materiel and extensive damage in high voltage, medium voltage as well as DC voltage hardware of the substation in addition to significant loss of load. This paper begins with an assessment of the power system condition at the time of the incident. Then the sequence of events for this accident will be described. The ensuing measures that include the restoration of interrupted power supply, the partial return to service as well as the final completion of repairs at the substation facility are detailed. The analysis of the incident is presented. Conclusions of practical importance are drawn as well as recommendations regarding improvements in hardware and protection system and in the available technical support that can be crucial in avoiding and/or limiting damage in future incidents.

Ključne riječi: jednofazni kratki spoj; kvar u električnoj mreži; zaštita transformatorske stanice,
Keywords: power grid incident; substation protection; single-phase fault

1 UVOD

Elektroenergetski sustav Krete je otočni sustav s 1 GW instalirane snage od čega 160 MW generiraju vjetroelektrane. Vršno opterećenje u 2008. godini bilo je 650,3 MW.

Predmet proučavanja je nedavan veliki kvar na elektroenergetskom sustavu Krete koji je za posljedicu imao veliku štetu na TS Iraklio 3, 150/15 kV (2008-06-29T05:00 – nedjelja ujutro). Havarija je započela kvarom na srednjem naponu u trafostanici. Taj kvar nije bio uklonjen zbog istodobnog uništenja zaštitnih i kontrolnih strujnih krugova što je za posljedicu imalo velike struje kratkog spoja tijekom 16 minuta, požare na opremi i veliku štetu na dijelu visokog napona, srednjeg napona kao i uređaja istosmjerne struje u transformatorskoj stanici, uz znatnu redukciju opterećenja. Udjel proizvodnje iz vjetroelektrana na početku kvara bio je značajan (22,5 %). Srećom, postajala je i znatna rotirajuća rezerva (42 %) tako da je posljedično isključeno samo 10 MW vjetroelektrana.

Ova analiza počinje ocjenom stanja ili uvjeta u elektroenergetskom sustavu u trenutku nastanka kvara. Potom se opisuje slijed događaja. Podrobno su opisane proizašle mjere koje uključuju ponovnu uspostavu opskrbe energijom, djelomičan povratak u pogon, kao i konačan dovršetak popravaka na objektu transformatorske stanice. Predstavljena je analiza kvara. Doneseni su zaključci od praktične važnosti kao i preporuke u odnosu na poboljšanja u hardverskom i zaštitnom sustavu te dostupnoj tehničkoj potpori, koja mogu biti presudna za izbjegavanje i/ili ograničavanje štete kod budućih kvarova.

Operativni su podaci prikupljeni korištenjem sustava SCADA, digitalnog releja na polju prekidača 150 kV P40 (slika 1) napojnog voda za TS Iraklio 3 i digitalnog oscilografa ROCHESTER instaliranog na parnoj jedinici broj 5 – oba u termoelektrani Linoperamata, zabilježenih podataka u elektrani Atherinolakos (istočni dio otoka), zabilježenih podataka na elektrani Xylokamara (zapadni dio otoka) te iz naknadnih nalaza iz TS Iraklio 3.

2 STANJE SUSTAVA NETOM PRIJE KVARA

Srećom, u trenutku incidenta, potražnja je bila relativno niska i iznosila je 312 MW (gotovo minimalno opterećenje) za cijeli otok. TS Iraklio 3 je bila opterećena sa 20 MW. Svaki od dva transformatora (svaki nominalne snage 50 MVA) transformatorske stanice bili su opterećeni s 8 MW, a

1 INTRODUCTION

The power system of Crete is an island system with 1 GW installed power out of which 160 MW are wind-power generation. It had a 650,3 MW peak demand in year 2008.

A recent major incident in the Electric Power System (EPS) of Crete resulting in extensive damages in the SS Iraklio 3, 150/15 kV (2008-06-29T05:00 – Sunday morning) is studied. The accident originated from a medium voltage fault at the substation. This fault was not cleared due to the coincident destruction of the protection and control circuits resulting in large short-circuit currents for 16 minutes, fires of materiel and extensive damage in high voltage, medium voltage as well as DC voltage hardware of the substation in addition to significant loss of load. There was substantial wind power penetration at the incident start (22,5 %). Fortunately, there was also substantial spinning reserve in parallel (42 %) so only 10 MW of wind were switched-off as a result.

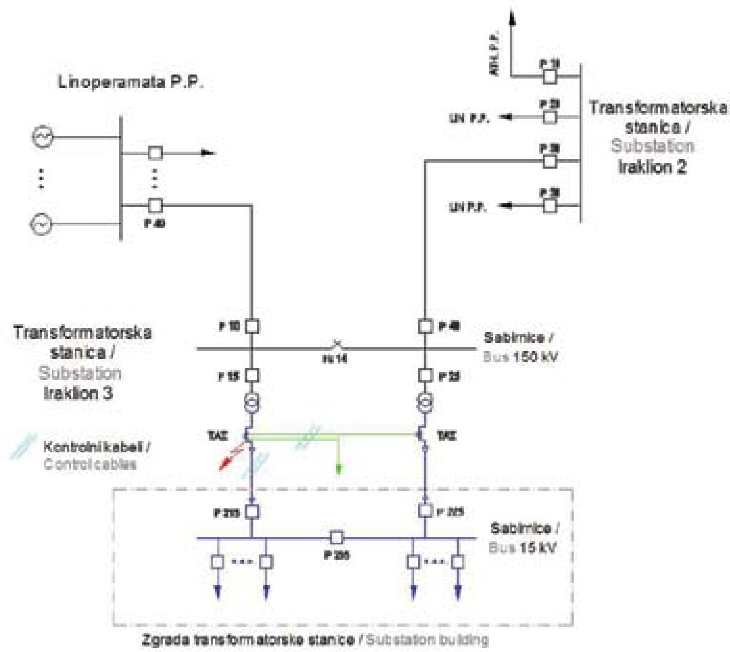
In this Presentation we begin with an assessment of the power system condition at the time of the incident. Then the sequence of events for this accident is described. The ensuing measures that include the restoration of interrupted power supply, the partial return to service as well as the final completion of repairs at the substation facility are detailed. The analysis of the incident is presented. Conclusions of practical importance are drawn as well as recommendations regarding improvements in hardware and protection system and in the available technical support that can be crucial in avoiding and/or limiting damage in future incidents.

Operational data were collected using the SCADA system, the digital relay at the 150 kV bay of the breaker P40 (Figure 1) of the feeder for the SS Iraklio 3 and the digital oscillograph ROCHESTER installed at the steam unit #5- both at Linoperamata power station, data registrations at the Atherinolakos power station (east part of the island), data registrations at the Xylokamara power station (west part of the island), and from post-mortem findings at the SS Iraklio 3.

2 SYSTEM STATE JUST BEFORE THE INCIDENT

Fortunately, at the time of the incident the demand was relatively low and amounted to 312 MW (near minimum load) for the whole island. There was a load of 20 MW from Iraklio 3 substation. Each of the two transformers (nominal power of 50 MVA preostalih 4 MW dolazilo je izravno iz vjetroparka Domiki Kritisa i napajalo je 15 kV sabirnice putem prekidača P270 (nije prikazan na slici 1).

each) of the substation were loaded with 8 MW, and the remaining 4 MW came directly from the Wind Park of Domiki Kritis fed to the 15 kV busbars via the breaker P270 (not shown in figure).



Slika 1 — Jednopolna shema TS Iraklion 3 s veznim stanicama
Figure 1 — Single-line diagram of SS Iraklion 3 with connecting stations

Zbog vremena u danu i očekivanog porasta opterećenja, postojala je znatna rotirajuća rezerva u trenutku incidenta koja je iznosila 138 MW (44,2 % od opterećenja), uz činjenicu da su jedinice koje su bile u pogonu u tom trenutku imale dovoljno kapaciteta za proizvodnju jalove snage. To je djelovalo povoljno i smanjilo je utjecaj kvara na opskrbu energijom (slika 2). Udjel vjetroelektrana stao je na 23 %. Bazne parne jedinice bile su u pogonu u tom trenutku kao i dizelske jedinice.

Due to the hour and the expected load increase, there was substantial spinning reserve at the time of the incident amounting to 138 MW (44,2 % of load demand), plus the fact that the units operating at the time had ample capacity for reactive power generation. This had been favorable and it reduced the overall impact of the incident on the load supply (Figure 2). The wind power penetration stood at 23 %. There were steam base units operating at the time and diesel units as well.

3 SLIJED DOGAĐAJA ZA VRIJEME KVARA

Crvene strelice na slici 1 pokazuju mjesto kvara. Kvar je očito počeo kao jednofazni kratki spoj koji se zbog posljedičnog uništenja dijela zaštite u 24 sekunde razvio u trofazni kratki spoj (slika 3).

Na slici 2, različite boje, odozdo prema gore, odgovaraju parnim jedinicama, kombiniranom ciklusu, dizelskim jedinicama, plinskim turbinama i vjetroelektranama.

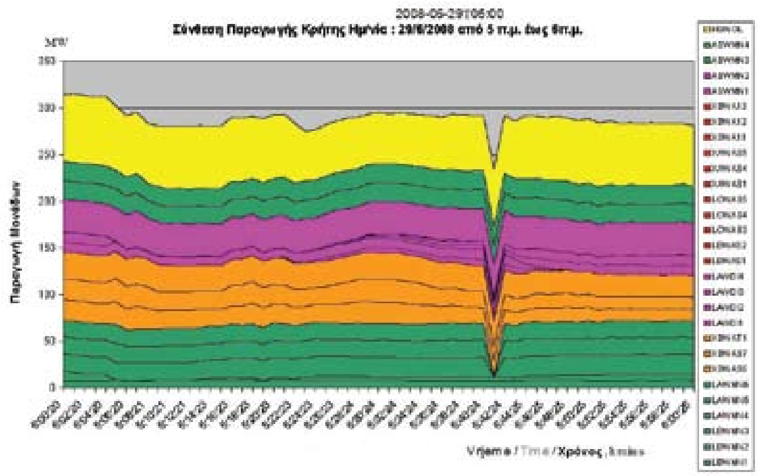
U kritičnom razdoblju došlo je do pada napona na visokonaponskim sabirnicama TS Iraklio 3 na

3 THE INCIDENT SEQUENCE OF EVENTS

The red arrows in Figure 1 show the position of the fault. The fault apparently started as a single-phase fault which due to the resulting destruction developed in 24 seconds into a three-phase fault (Figure 3).

In Figure 2, different colors, from base upwards, correspond to steam units, combined cycle, diesel units, gas turbines, and wind generation.

In the critical period there was a voltage drop at the HV busbars of SS Iraklio 3 to 130,61 kV, while at Ath-



Slika 2 — Opskrba opterećenjem (vremenski graf u h:min:s) uključujući i poremećaj po incidentu

Figure 2 — Load supply (time-graph in h:min:s) including the incident disturbance

130,61 kV, dok je u Atherinolakosu (zapadna strana otoka) pao na 143 kV gdje je parna jedinica broj 1 (nominalne snage 50 MW) proizvodila 20 MW i 0,74 Mvar prije kvara – porasla je na 42,2 Mvar nakon kvara i kasnije se ustalila na 20 Mvar. Mogućnost proizvodnih jedinica da povećaju proizvodnju jalove snage pomogla je održanju prihvatljivih razina napona i tako je izbjegnut opći raspad. Na slici 3 se mogu vidjeti linijski naponi kod jedinice Atherinolakos broj 1 kao i proizvodnja djelatne i jalove snage u vremenu oko kvara.

Na slici 4 može se vidjeti proizvodnja jalove snage dvije plinske turbine u postrojenju kombiniranog ciklusa Xylokamara (istočna strana Krete). Ponovno se može vidjeti povećanje proizvodnje jalove snage u kritičnom razdoblju – koje je išlo gotovo od 0 Mvar na 23,145 Mvar i 22,998 Mvar za pojedinu plinsku turbinu.

Na slici 5 može se vidjeti napon i frekvencija izmjereni na TS Iraklio 2. Vidi se da je na početku kvara, zbog gubitka dvije jedinice (parne jedinice broj 3 Linoperamata sa 7 MW opterećenja, i dizelske jedinice broj 4 Linoperamata s 10,5 MW opterećenja), frekvencija pala na minimum od 49,53 Hz.

Ukupna neisporučena energija radi podfrekvencijske zaštite (u razdoblju između 21. i 25. min) iznosila je 7,6 MWh.

Neisporučena energija zbog kvara na TS Iraklio 3 iznosila je 46,6 MWh. Prekid opskrbe potrošača trajao je između 2 sata i 45 minuta do maksimalno 3 sata i 32 minute.

erinolakos (west-side of the island) fell to 143 kV where the steam unit #1 (nominal power 50 MW) was generating 20 MW and 0,74 Mvar before the incident – went up to 42,2 Mvar after the incident and leveled-off at 20 Mvar later. The capacity of the units to increase their reactive generation helped in sustaining voltage levels acceptable and to avoid a general blackout. In Figure 3 we can see the line-voltages at the Atherinolakos unit #1 as well as the real and reactive power generation around the incident.

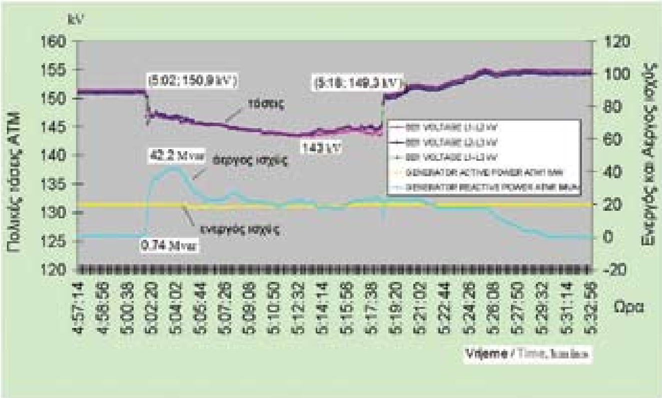
In Figure 4 we can see the reactive power generation of the two gas turbines of the combined-cycle unit at Xylokamara power station (east-side of Crete). Again we see the increased reactive power generation at the critical period, which increased from close to 0 Mvar before the incident to 23,145 Mvar and 22,998 Mvar for each turbine.

In Figure 5 we can see the voltage and the frequency measured at the SS Iraklio 2. We see that at the beginning of the incident, because of the loss of two power units (steam unit #3 Linoperamata with 7 MW load, and Diesel unit #4 Linoperamata with 10,5 MW load), the frequency dropped to a minimum of 49,53 Hz.

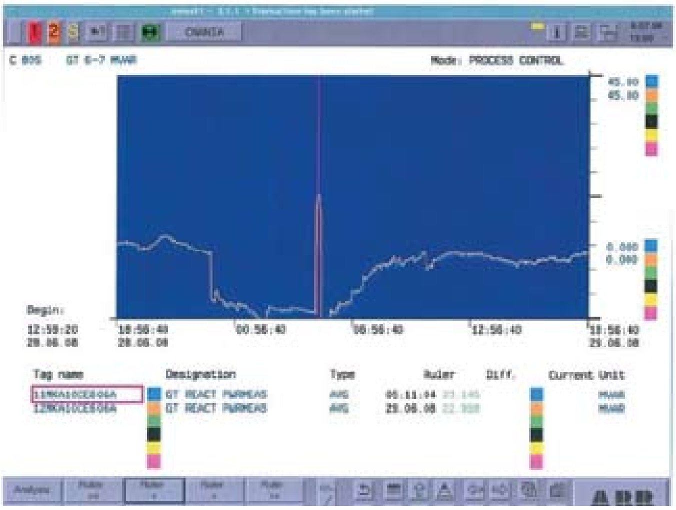
We note that the total energy loss due to underfrequency-protection load shedding (lasting from 21 to 25 min) amounted to 7,6 MWh.

The energy lost due to the destruction of SS Iraklio 3 amounted to 46,6 MWh. The power cuts to consumers lasted from 2hrs 45 min up to 3hrs 32 min maximum.

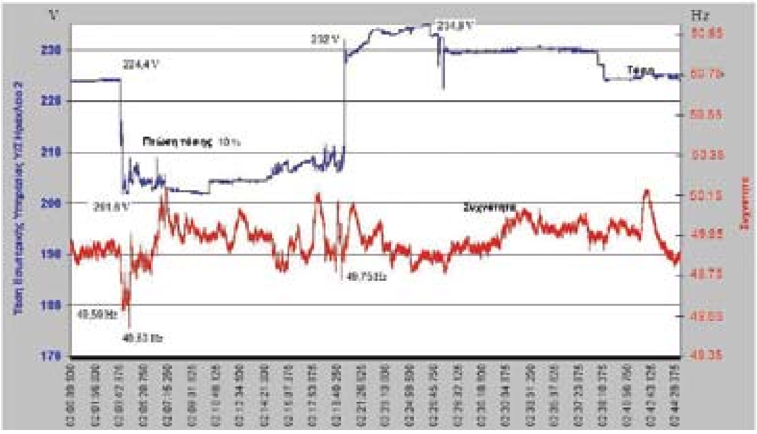
Figure 5



Slika 3 — Linijski naponi, djelatna i jalova snaga parne jedinice 1 u elektrani Atherinolakos
Figure 3 — Line voltages, real and reactive power of steam unit 1 – Atherinolakos PS



Slika 4 — Jalova snaga plinskih turbina u postrojenju kombiniranog ciklusa u Xylokamari
Figure 4 — Reactive power of GTs of Combined cycle unit at Xylokamara



Slika 5 — Vremenski grafovi napona i frekvencije izmjereni na TS Iraklio 2
Figure 5 — Voltage and frequency time-graphs measured at Iraklio 2 substation

4 ANALIZA DOGAĐANJA

Istraga nakon događaja pokazala je da je kvar počeo kao jednofazni kratki spoj srednjenaponskog kabela koji je povezivao sekundar prvog transformatora TS Iraklio 3, samo od točke podzemnog ulaska kabela. Bio je to kvar visokog otpora za koji se zna da ne uključuje diferencijalnu zaštitu transformatora. Zbog topline koju je proizveo kvar, izgorjele su izolacije niskonaponskih kabela zaštite čvorišta kondenzatora koji su bili u blizini te je stoga srednji napon bio prenesen na polje kondenzatora uzrokujući potpuno uništenje zbog topline i požara. Osim toga, srednji napon je prenesen na sve zaštitne i kontrolne krugove transformatorske stanice.

Ubrzo nakon toga kvar se razvio u trofazni kratki spoj i izazvao da diferencijalna zaštita transformatora otvori prekidač P215 (slika 1) na sekundarnoj strani transformatora, no nije uspjela otvoriti prekidač P15 (ista slika) zbog uništenja pripadajućeg okidača strujnog kruga. Drugim riječima, kvar nije bio uklonjen. Procjenjuje se da su struje kratkog spoja iznosila 4 933 A. Te su struje tekle neprekidno 16 minuta, stvarajući destruktivnu toplinu koja je rezultirala raširenim požarom na instalacijama transformatorske stanice. Krajnji je rezultat bila značajna šteta na energetskom transformatoru broj 1 transformatorske stanice, te uništenje sve kontrolne i zaštitne opreme, uključujući jedan interni transformator za servisni napon, tri audiofrekvencijska transformatora, itd.

5 PREPORUKE

Poukom ovog iskustva, smatra se obaveznim odvojiti energetske kabele od kontrolnih i zaštitnih kabela provodeći ih kroz potpuno različite kanale. Također, savjetuju se povratne zaštite (engl. back-up) transformatora. Na primjer, trebala bi postojati povratna zaštita u slučaju da diferencijalna zaštita ne djeluje. Stoga bi trebalo uvesti nadstrujnu zaštitu, uz nešto veći vremenski interval, na visokonaponskom prekidaču transformatora. Nadalje, bila bi nužna zaštita od zemljospoja koja je osjetljivija na jednofazne kratke spojeve.

Također, smatra se nužnim dodatno istražiti učinkovitost rada digitalnih distantnih releja korištenih u sustavu.

4 THE ANALYSIS OF WHAT HAD HAPPENED

From the post-mortem on-site investigation it became apparent that the fault began as a single-phase MV cable fault connecting the secondary of the first transformer of SS Iraklio 3, just 5 m away from the point of the subterranean entrance of the cable. It was a high resistance fault that is known not to energize the transformer differential protection. Due to the heat produced by this fault, the LV cables of the capacitor node-protection, which were in the vicinity, had their insulations burnt, and therefore the MV was transmitted to the capacitor bay causing complete destruction due to heat and fire. In addition the MV had been transmitted to all the protection and control circuits of the substation.

Shortly afterwards, the fault developed into a three-phase fault causing the differential transformer protection to open the circuit breaker P215 (Figure 1) on the transformer secondary side, but, it failed to open the breaker P15 (same figure) due to the destruction of the corresponding trip-circuit. In other words, the fault failed to be cleared. The fault currents have been estimated to 4 933 A. These currents were sustained for 16 continuous minutes, producing destructive heat that resulted in extensive fires in the substation installations. The end result was that Power Transformer # 1 of the substation suffered extensive damage, as had all the control and protection equipment, including one internal service transformer, three audio-frequency transformers, etc. which were destroyed.

5 RECOMMENDATIONS

Following this experience, it is considered a must to separate the power cables from the control and protection cables passing them through completely different channels. Moreover, back-up transformer protections are advisable. For example, there should be a back-up protection in case differential protection fails to act. So, a high-current protection should be enacted, at a slightly higher time-interval, at the HV breaker of the transformer. In addition, a restricted earth-fault protection could be necessary, which is more sensitive to single-phase faults.

A further investigation of the effectiveness of operation of the digital distance relays, used in the system, is also deemed necessary.

6 ZAKLJUČCI

Opisan je težak kvar u radu elektroenergetskog sustava Krete 2008. godine. Kvar je izazvao veliku štetu na TS Iraklio 3, znatan poremećaj rada i prekid u opskrbi energijom. Predstavljena je analiza slijeda i uzroka događaja. Iznesene su preporuke u smislu pouzdanijeg rada i izgradnje postrojenja.

6 CONCLUSIONS

A destructive incident in the operation of the electric power system of Crete in 2008 has been presented. The fault caused extensive damages at the SS Iraklio 3, substantial disruption of service, and loss of energy delivery. An analysis of what and how it happened was presented. Recommendations were drawn for practical as well as design purposes.

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ESTIMACIJA KUTA OPTEREĆENJA SINKRONOG GENERATORA DINAMIČKIM NEURONSKIM MREŽAMA

LOAD ANGLE ESTIMATION OF A SYNCHRONOUS GENERATOR USING DYNAMICAL NEURAL NETWORKS

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Definiran je postupak estimacije kuta opterećenja sinkronog generatora u radu na elektroenergetski sustav zasnovanog na dinamičkim neuronskim mrežama. U postupku formiranja estimacijskog modela istražen je i definiran izbor ulaznih veličina i struktura dinamičke neuronske mreže. Za učenje dinamičke neuronske mreže koriste se podaci iz snimljenih odziva u ustaljenom pogonskom stanju i pri poremećajima u radu sinkronog generatora na mrežu. Usporedbom rezultata dobivenih primjenom definiranog postupka estimacije kuta opterećenja, s rezultatima dobivenim mjerenjem, pokazana je primjenjivost predloženog estimacijskog postupka zasnovanog na dinamičkim neuronskim mrežama.

Load angle estimation process of the operating synchronous generator on the power system is defined based on dynamic neural networks. In the process of forming the estimation model the choice of input values and structures of dynamic neural network is explored and defined. Data from recorded responses to the network at standard operating conditions and at malfunctioning of a synchronous generator are used for learning the dynamic neural network. The comparison of the results obtained using the defined method of load angle estimation with the results obtained by measurement, reveals the applicability of the proposed estimation method based on dynamic neural networks.

Ključne riječi: dinamička neuronska mreža; estimacija; kut opterećenja; sinkroni generator
Key words: dynamic neural network; estimation; load angle; synchronous generator

1 UVOD

Kut opterećenja sinkronog generatora u radu na elektroenergetski sustav (EES) pogonska je veličina koja daje praktički direktni podatak o položaju radne točke generatora u odnosu na granicu stabilnosti. Rad EES-a karakteriziraju velike promjene pogonskog režima rada sinkronog generatora, tako da prijelaz iz jednog u drugo ustaljeno pogonsko stanje najčešće prate značajne dinamičke promjene kuta opterećenja. Ovo rezultira promjenom kuta opterećenja, u relativno kratkom vremenu, u rasponu od maksimalnog do minimalnog iznosa.

Vrijednost kuta opterećenja posebno je važan podatak u slučaju da generator radi u poduzbuđenom stanju, jer tada kut opterećenja poprima maksimalno dopuštene vrijednosti u odnosu na granicu stabilnosti rada sinkronog generatora.

Podatak o kutu opterećenja može se koristiti za zaštitu od ispada generatora pri radu u kapacitivnom pogonskom području, a također moguća je i primjena u realizaciji stabilizatora EES-a, gdje se promjena kuta opterećenja može koristiti kao ulazni signal stabilizatora.

Izravno mjerenje kuta opterećenja generatora primijenjeno je u relativno malo slučajeva. Zato se kut opterećenja određuje neizravno, temeljem raspoloživih mjerenih veličina. Jedan od načina je određivanje kuta opterećenja sinkronog generatora iz podataka dobivenih mjerenjem mehaničkog kuta rotora generatora i električnog kuta osnovnog harmonika okretnog magnetskog polja, pri čemu vrijednost kuta predstavlja razliku između ove dvije veličine. Nedostatak ovog načina određivanja kuta opterećenja sinkronog generatora je u tome što traži dodatna mjerenja, a time i ugradnju dodatne mjerne opreme.

Drugi način je određivanje kuta opterećenja primjenom estimacijskih postupaka koji koriste raspoložive mjerene električne veličine koje su već uvedene za potrebe regulacije sustava uzbude. Ovi postupci se češće primjenjuju, posebno na suvremenim digitaliziranim regulatorima sustava uzbude, gdje se estimacija realizira s raspoloživim mjerenjima kao dodatna (programska) funkcija regulatora.

Takvi postupci estimacije zahtijevaju poznavanje parametara nadomjesne mreže, parametara generatora i uvođenje zasićenja u matematički model sinkronog generatora, a estimacija kuta opterećenja sinkronog generatora najčešće se realizira primjenom odgovarajućih estimacijskih modela i algoritama [1], [2], [3] i [4].

1 INTRODUCTION

The load angle of the operating synchronous generator on the power supply system (PPS) is the operational value which provides virtually direct information about the generator working point position in relation to the stability limit. The functioning of the PPS is characterized by significant changes in synchronous generator functioning, so that the transition from one to another steady operating condition is often accompanied by significant changes in the dynamic load angle. This results in changes of the load angle, in a relatively short period of time, from the maximum to the minimum amount.

The load angle value is especially important information in case when the generator operates in subexcitation state, because then the load angle assumes the maximum allowed value in relation to the stability limit of synchronous generator operation.

Load angle data can be used for protection against generator outage during its functioning in capacitive operating mode, and application is also possible in the implementation of the PPS stabilizer, where the change of the load angle can be used as a stabilizer input signal.

Direct generator load angle measurement is applied in a relatively small number of cases. Therefore, the load angle is indirectly determined, based on available measured values. One of the methods is to determine the load angle of the synchronous generator from the data obtained by measurement of the generator rotor mechanical angle and the electrical angle of the base accordion of the rotating magnetic field, whereby the angle value is the difference between those two sizes. A disadvantage of this method of determination of the load angle of the synchronous generator is that additional measurements and installation of additional measuring equipment are required.

Another method is to determine the load angle by implementing estimation procedures which use the available measured electrical values that have been already introduced for the purpose of the excitation system regulation. These procedures are applied more often, particularly on modern digital regulators of the excitation system, where the estimation is implemented with the available measurements as additional (program) regulator function.

These estimation methods require knowledge of parameters of the equivalent network, the generator parameters and the introduction of saturation in the mathematical model of synchronous generator while the load angle estimation of the synchronous generator is usually implemented by using appropriate estimation models and algorithms [1], [2], [3], [4].

Osnovi nedostatak primjene ovakvog estimacijskog postupka u određivanju kuta opterećenja sinkronog generatora je potreba za poznavanjem parametara generatora (reaktancije) i poznavanje parametara nadomjesne električne mreže.

Primjenom estimacijskog postupka zasnovanog na neuronskim mrežama ovaj nedostatak može se otkloniti. Za ostvarenje postupka estimacije zasnovanog na neuronskim mrežama potrebna je neuronska mreža odgovarajuće strukture i algoritam za učenje neuronske mreže.

U ovom radu pokazan je postupak estimacije kuta opterećenja sinkronog generatora zasnovan na dinamičkim neuronskim mrežama. Primjena neuronskih mreža, za razliku od prije spomenutih postupaka ne zahtijeva poznavanje parametara nadomjesne mreže i parametara sinkronog generatora što smanjuje pogreške koje se javljaju u postupcima estimacije kuta opterećenja.

S druge strane, dinamička neuronska mreža za razliku od statičkih ima bolju sposobnost aproksimacije realnih dinamičkih sustava kakav je i EES, što naročito dolazi do izražaja pri poremećajima u radu sinkronog generatora.

2 STRUKTURA ESTIMACIJSKOG POSTUPKA

Za estimaciju kuta opterećenja potreban je matematički model sinkronog generatora iz kojeg se vidi međusobna povezanost pogonskih veličina. Na osnovi takvog modela može se formirati model sinkronog generatora zasnovan na neuronskim mrežama. Za model sinkronog generatora, koji je zasnovan na neuronskim mrežama, potrebno je odabrati skup ulaznih veličina koje su u potrebnoj mjeri informativne da se odgovarajućom strukturom primijenjene neuronske mreže dobije zadovoljavajuća točnost estimacije.

Formiranje estimacijskog modela zasnovanog na neuronskim mrežama u osnovi je heuristički postupak, jer polazi od pretpostavke da će skup odabranih ulaznih veličina biti dovoljan za estimaciju, zbog čega je potrebno provesti provjeru postupka estimacije na realnom sustavu za sva pogonska stanja definirana pogonskom kartom.

2.1 Matematički model sinkronog generatora

Matematički model sinkronog generatora u radu na mrežu prema [5], [6] i [7] formiran je tako da koristi ulazne veličine dostupne standardnim mjerenjima u pogonu: napon na izvodima generatora U_G, struja generatora I_G i struja uzbude

The basic disadvantage of this estimation method of determining the load angle of the synchronous generator is that generator parameters (reactance) and equivalent electrical power installation parameters need to be known.

By applying the estimation process based on neural networks this disadvantage can be eliminated. To accomplish the estimation procedure based on neural networks, an appropriate neural network structure and neural networks learning algorithm are required.

This paper presents the synchronous generator load angle estimation method based on dynamic neural networks. Application of neural networks, unlike the above mentioned procedures, does not require knowledge of the equivalent network parameters and synchronous generator parameters which reduces errors that occur in the methods of load angle estimation.

On the other hand, a dynamic neural network, as opposed to the static, has better ability of approximations of real dynamic systems like the PPS, which is especially evident at disturbances during synchronous generator operation.

2 STRUCTURE OF THE ESTIMATION METHOD

A mathematical model of the synchronous generator, from which the coherence of operational values can be seen, is required for load angle estimation. On the basis of such model, the synchronous generator model can be formed based on neural networks. For the synchronous generator model which is based on neural networks, it is necessary to choose a set of input values which are informative to the necessary extent, so that satisfactory accuracy of estimation with the appropriate structure of the applied neural network can be obtained.

Forming of the estimation model based on neural networks is fundamentally heuristic procedure, because it is based on the assumption that the set of selected input values will be sufficient for estimation, and therefore it is necessary to conduct verification of the estimation process on the real system for all operating conditions defined by the operative map.

2.1 The mathematical model of the synchronous generator

The mathematical model of the synchronous generator operating on the network, according to [5], [6] and [7], is formed so as to use the input values available through standard measurements at operation:

I_{fd}. Na ovaj način formirani matematički model može se opisati sustavom jednadžbi sinkronog generatora:

voltage at the generator terminals U_G, generator current I_G and excitation current I_{fd}. In this way, the created mathematical model can be described by the synchronous generator equations system:

$$\frac{d\delta}{dt} = (\omega - 1)\,\omega_s \,, \tag{1}$$

$$\frac{d\omega}{dt} = \frac{1}{2H}\left[T_m - T_{el} - K_D\,(\omega - 1)\right], \tag{2}$$

$$\frac{dE_q^{'}}{dt} = \frac{1}{T_{d0}^{'}}\left[E_q^{'} - \left(x_d - x_q^{'}\right) I_d + E_{fd}\right], \tag{3}$$

gdje su:

- δ – kut opterećenja,
- ω – kutna brzina,
- ω_S – sinkrona brzina vrtnje generatora,
- H – konstanta tromosti,
- T_m – mehanički moment pogonskog stroja,
- T_{el} – električki moment generatora,
- K_D – koeficijent prigušenja,
- E'_q – napon iza x_q reaktancije,
- E_{fd} – napon uzbude,
- T''_{d0} – vremenska konstanta uzbude uz otvorenu armaturu i bez djelovanja prigušnog namota,
- x_d – uzdužna reaktancija,
- x_q – poprečna reaktancija.

Struja uzbude I_{fd} uvodi se u model sa:

where:

- δ – load angle,
- ω – angle speed,
- ω_S – generator synchronous speed,
- H – sloth constant,
- T_m – mechanical torque of engine,
- T_{el} – electrical torque of generator,
- K_D – attenuation coefficient,
- E'_q – voltage beyond x_q reactance
- E_{fd} – excitation voltage
- T''_{d0} – excitation time constant with open armouring and without working of attenuation coil,
- x_d – longitudinal reactance,
- x_q – transverse reactance.

Excitation current I_{fd} is introduced into the model with:

$$E_q^{'} = -\frac{(x_d - x_l)^2}{\left[(x_d + x_{fd}) - x_l\right]^2} I_d + (x_d - x_l)\cdot I_{fd}, \tag{4}$$

gdje su:

- x_d – rasipna reaktancija armature,
- x_{fd} – reaktancija uzbudnog kruga.

where:

- x_d – armouring dissipate reactance,
- x_{fd} – excitation circuit reactance.

Komponente napona sinkronog generatora u d-osi i q-osi U_d i U_q, nakon transformiranja u d-q sustav koji rotira sinkronom brzinom, određuju se prema:

Synchronous generator voltage components in the d-axis and q-axis U_d and U_q, after transforming in the d-q system that rotates with synchronous speed, are determined according to:

$$\begin{aligned} U_d &= U_G \sin(\delta) \\ U_q &= U_G \cos(\delta) \end{aligned} \tag{5}$$

U postavljenome matematičkom modelu varijable I_d i I_q koje predstavljaju komponente struje armature u d-osi i q-osi određuju se iz:

In the designated mathematical model, I_d and I_q variables that represent components of the armouring current in the d-axis and q-axis are determined based on:

$$P_G = U_d I_d + U_q I_q$$
$$Q_G = -U_q I_d + U_d I_q \quad , \qquad (6)$$

gdje su vrijednosti veličina P_G i Q_G određene mjerenjem.

where P_G and Q_G values are determined with measurement.

Veza između mjerljivih struja i napona i njihovih komponenti u d-osi i q-osi je:

The connection between the measurable currents and voltages and their components in the d-axis and q-axis is:

$$U_G^2 = U_d^2 + U_q^2, \qquad (7)$$

$$I_G^2 = I_d^2 + I_q^2. \qquad (8)$$

Prema [1] može se napisati:

According to [1] it can be written:

$$U_d = x_q \cdot I_q \ , \qquad (9)$$

$$U_q = x_d \cdot I_d + x_{ad} \cdot I_{fd} \, . \, . \qquad (10)$$

Uvrštavanjem (9) i (10) u (6), u matematički model sinkronog generatora se uvode, kao što je na početku spomenuto, mjerljive veličine U_G, Q_G, I_{fd} i na taj način komponenta napona generatora U_q izražen preko mjerljivih veličina je:

The inclusion of (9) and (10) in (6), in the mathematical model of the synchronous generator , as mentioned at the beginning, measurable values U_G, Q_G, I_{fd}, and thus the generator voltage component U_q expressed by virtue of measurable quantities are introduced:

$$U_q = \frac{\left(\frac{x_{ad}}{x_d} I_{fd}\right) + \sqrt{\left(\frac{x_{ad}}{x_d} I_{fd}\right)^2 + 4\left(\frac{1}{x_q} - \frac{1}{x_d}\right)\left(Q_G + \frac{U_G^2}{x_q}\right)}}{2\left(\frac{1}{x_q} - \frac{1}{x_d}\right)}. \qquad (11)$$

Potrebno je napomenuti da u realnom sustavu komponenta napona u q-osi U_q je pozitivna realna vrijednost pa se drugo rješenje jednadžbe (11) odbacuje. Realna vrijednost rješenja proizlazi iz odnosa sinkronih reaktancija u d i q osi $x_d > x_q$. Kada se odredi komponenta napona generatora u q-osi U_q jednostavno je odrediti i komponentu napona u d-osi U_d.

It is necessary to mention that in the real system, the voltage component in the q-axis U_q is a positive real value so that the second solution of the equation (11) is rejected. Real-valued solution is derived from the relationship between synchronous reactance in the d and q axes $x_d > x_q$. When the generator voltage component is determined in the q-axis U_q it is easy to specify the voltage component in the d-axis U_d.

Kut opterećenja generatora može se odrediti iz (5):

The generator load angle can be calculated from (5):

$$\delta = \arc \cos \frac{U_q}{U_G} \,. \tag{12}$$

Kako se vidi u (11) i (12) postoji ovisnost kuta opterećenja generatora o osnovnim električkim veličinama koje su standardno mjerljive na izvodima generatora, a temeljem kojih su dobivene vrijednosti za djelatnu i jalovu snagu generatora, tako da je kut opterećenja funkcija ovih veličina: $\delta = f(P_G, Q_G, I_{fd})$. Također se može pretpostaviti da je ovaj skup fizikalnih veličina (P_G, Q_G, I_{fd}) dovoljno informativan da bi se primjenom neuronskih mreža mogao estimirati kut opterećenja generatora.

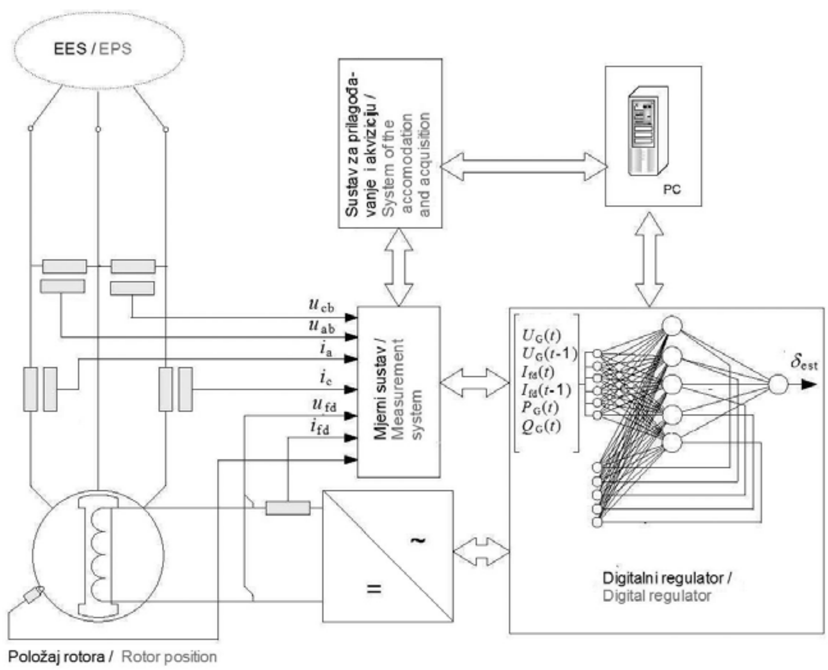
2.2 Sustav za estimaciju kuta opterećenja sinkronog generatora

Na slici 1 pokazana je blokovska shema regulatora sustava uzbude s dodanom funkcijom estimacije kuta opterećenja. Za potrebe regulacije sustava uzbude mjere se struje i naponi armaturnog namota i struja i napon uzbude generatora. Iz mjerenih napona i struja armaturnog namota određuje se napon generatora U_G, djelatna P_G i jalova Q_G snaga, dok se struja uzbude I_{fd} mjeri izravno. Ovi signali koriste se kao ulazne veličine za regulaciju napona generatora, a u ovom radu iskorištene su i za estimaciju kuta opterećenja generatora.

As shown in (11) and (12), there is a generator load angle dependence on the basic electrical values which are measurable on the generator terminals by default, based on which values of the active and reactive powers of the generator are obtained, so that the load angle is the function of these values: $\delta = f(P_G, Q_G, I_{fd})$. It can also be assumed that this set of physical values (P_G, Q_G, I_{fd}) is sufficiently informative to use the neural networks for the estimation of the generator load angle.

2.2 The system for load angle estimation of the synchronous generator

Figure 1 shows the block scheme of the excitation system regulator with the addition of the load angle estimation function. For the purposes of excitation system regulation, currents and voltages of armouring winding and the excitation current and voltage of the generator are measured . From the measured voltage and current values of armouring winding, the generator voltage U_G, active P_G and reactive Q_G powers are determined, while the excitation current I_{fd} is measured directly. These signals are used as input values for regulation of the generator voltage, and in this paper these are used for the generator load angle estimation.



Slika 1 — Estimacija kuta opterećenja neuronskom mrežom
Figure 1 — Neural network load angle estimation

Za estimaciju kuta opterećenja potrebno je provesti jednokratno mjerenje kuta opterećenja pri različitim pogonskim stanjima generatora, tako dobiveni podaci koriste se za učenje neuronske mreže.

Za potrebe ovog rada razvijen je i izrađen mjerni sustav koji se sastoji od:

- osjetnika prolaza rotora generatora kroz zadani položaj,
- detektora prolaza napona kroz nulu i
- mjerača vremena.

Kut opterećenja dobiven je mjerenjem vremena trajanja impulsa kojemu je prednji brid sinkroniziran s prolazom rotora kroz određeni položaj, a zadnji brid s prolazom osnovnog harmonika napona jedne faze kroz nulu. Dobiveno vrijeme trajanja impulsa proporcionalno je kutu opterećenja.

Estimacija kuta opterećenja ostvarena je primjenom dinamičke neuronske mreže, učenje neuronske mreže ostvareno je na osobnom računalu, nakon učenja kopija neuronske mreže kao skup parametara prenosi se na mikroračunalni sustav digitalnog regulatora i postavlja u funkciju estimacije kuta opterećenja.

2.3 Estimacija kuta opterećenja dinamičkom neuronskom mrežom

Ulazne veličine u estimacijski model odabrane su temeljem provedenih istraživanja [8], [9] heurističkim pristupom. Kako je prikazano na slici 1 na ulaze neuronske mreže dovedeni su:

- napon generatora $U_G(t)$,
- struja uzbude $I_{fd}(t)$,
- djelatna $P_G(t)$,
- jalova $Q_G(t)$ snaga generatora,
- prethodno stanje napona generatora $U_G(t-1)$ i
- prethodno stanje struje uzbude $I_{fd}(t-1)$.

Primijenjena je dvoslojna dinamička neuronska mreža, koja ima jedan skriveni sloj s nelinearnim (engl. *tansig*) neuronima i izlazni sloj s jednim linearnim neuronom.

Na slici 2 pokazana je dinamička neuronska mreže s dva sloja. Prvi skriveni sloj sastoji se od neurona s bipolarno sigmoidalnom aktivacijskom funkcijom. U skrivenom sloju ostvareno je povratno djelovanje, tako da se na ulaz sloja dovodi i vektor prethodnog stanja izlaznih signala skrivenog sloja. Vrijednosti težinskih koeficijenata skrivenog sloja dane matricom $\boldsymbol{W}^{1i}$. Težinski koeficijenti neurona dani su kao redak matrice $\boldsymbol{W}^{1i}$, tako da je broj redaka matrice $\boldsymbol{W}^{1i}$ jednak broju neurona u skrivenom sloju. Broj elemenata u retku matrice $\boldsymbol{W}^{1i}$ jednak je broju sinaptičkih veza pojedinog

For load angle estimation it is necessary to undertake a one-time measurement of the load angle at different generator operating conditions; information obtained in such way is used for learning neural networks.

For the purposes of this paper a measuring system is developed and manufactured that consists of:

- sensor of the generator rotor passage over the given position,
- detector of voltage passage through zero and
- timer.

The load angle is obtained by measuring the time duration of impulse the front edge of which is synchronized with the rotor passage through a certain position, and the last edge with the passage of the one-phase basic voltage harmonic through zero. The obtained impulse duration is proportional to the load angle.

Load angle estimation is achieved by using the dynamic neural network; neural network learning is realized on a PC; after learning, a copy of the neural network as a set of parameters is transferred to the digital regulator microprocessor system and the load angle estimation function sets in.

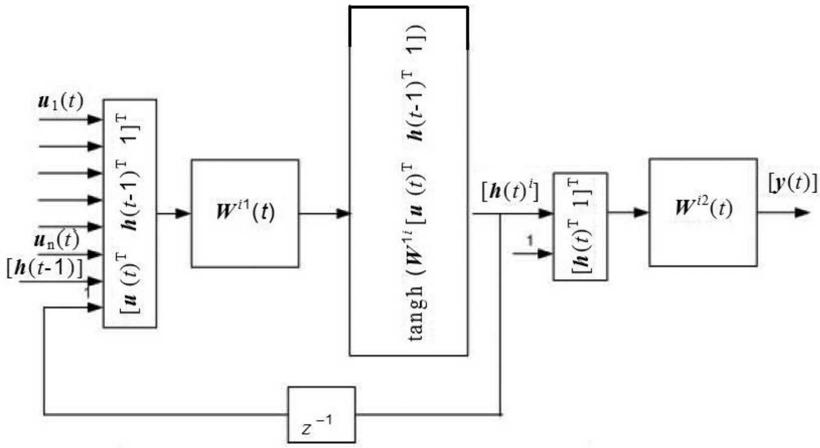
2.3 Dynamic neural network load angle estimation

Estimation model input values were selected based on previously conducted researches [8] and [9] by heuristic approach. As shown in figure 1, inputs have been brought to the neural networks:

- generator voltage $U_G(t)$,
- excitation current $I_{fd}(t)$,
- active $P_G(t)$,
- reactive $Q_G(t)$ power of the generator,
- previous voltage state of the generator $U_G(t-1)$ and
- previous state of excitation current $I_{fd}(t-1)$.

A double dynamic neural network is applied and it has one hidden layer with non-linear (*tansig*) neurons and an output layer with one linear neuron.

Figure 2 shows a dynamic neural network with two layers. The first hidden layer consists of neurons with bipolar sigmoid activation function. In the hidden layer reversible operation is achieved so that the vector of the previous states of the hidden layer output signals is brought onto the layer input. Values of hidden layer weight coefficients are given by the matrix $\boldsymbol{W}^{1i}$. Weight coefficients of neurons are given as a matrix row $\boldsymbol{W}^{1i}$, so that the number of matrix rows $\boldsymbol{W}^{1i}$ is equal to the number of neurons in the hidden layer. The number of elements in the matrix row $\boldsymbol{W}^{1i}$ is equal



Slika 2 — Dinamička neuronska mreža s jednim skrivenim slojem
Figure 2 — Dynamic neural network with one hidden layer

neurona. Broj sinaptičkih veza jednak je zbroju dimenzija vektora ulaza i dimenzija vektora povratnog djelovanja uvećanog za jedan.

Drugi sloj neuronske mreže je izlazni, a sastoji se od neurona s linearnom aktivacijskom funkcijom. Vrijednosti težinskih koeficijenata izlaznog sloja dane su matricom W^{2i} u kojoj je broj stupaca jednak broju neurona skrivenog sloja uvećano za jedan, dok je broj redaka jednak dimenziji izlaznog vektora $y(t)$.

Iznos izlaznog signala iz neuronske mreže je:

to the number of synaptic connections of each neuron. The number of synaptic connections is equal to the sum of the dimensions of the vector inputs and vector dimensions of reversible operation increased by one.

The second layer of the neural network is the output, and consists of neurons with linear activation function. Values of output layer weight coefficients are given by the matrix W^{2i} in which the number of columns is equal to the number of hidden layer neurons increased by one, while the number of rows is equal to the dimension of the output vector $y(t)$.

The output signal from the neural network is:

$$y(t) = W^{2i}\left[h^i(t)^T 1\right]^T , \tag{13}$$

gdje je:

$y(t)$ – vektor izlaznih signala,
W^{2i} – matrica težinskih koeficijenata izlaznog sloja,
$[h(t)^T 1]^T$ – vektor ulaznih signala u izlazni linearni sloj neuronske mreže, a sastoji se od izlaznih signala skrivenog sloja $h(t)$ proširenog s pomakom jediničnog iznosa (engl. *bias*).

Izlaz iz skrivenog sloja određuje se primjenom bipolarne sigmoidalne aktivacijske funkcije (tangh) nad umnoškom matrice težinskih koeficjenata W^{1i} i vektora $[u(t)^T h(t-1)^T 1]^T$ koji se sastoji od vektora ulaza u neuronsku mrežu $u(t)$, vektora prethodnog stanja izlaza iz skrivenog sloja $h(t-1)$ i pomakom jediničnog iznosa:

where:

$y(t)$ – vector of output signals,
W^{2i} – output layer weight coefficients matrix,
$[h(t)^T 1]^T$ – vector of input signals in the output linear layer of the neural network, and consists of the output signals of the hidden layer $h(t)$ expanded by the shift of unit amounts (bias).

The hidden layer output is determined by applying the bipolar sigmoid activation function (tangh) of the product of weights coefficient matrix W^{1i} and the vector $[u(t)^T h(t-1)^T 1]^T$ which consists of the vector of the inputs into the neural network $u(t)$, the vector of the previous state of the hidden layer output $h(t-1)$ and the shift of the unit amount:

$$h(t) = \tanh\left(W^{1i} \left[u(t)^{\mathrm{T}}\ h^{i}(t-1)^{\mathrm{T}}\ 1 \right]^{\mathrm{T}} \right) . \quad (14)$$

Učenje neuronske mreže, u postupku estimacije, ostvaruje se po metodi nadgledanog učenja, gdje se neuronska mreža uči s primjenom ulaznih veličina $\boldsymbol{u}(t)$ mjerenih na realnom sustavu. Nadgledanje postupka učenja ostvaruje se primjenom veličine $\boldsymbol{y}_{\mathrm{m}}(t)$ koja se dobiva također mjerenjem na realnom sustavu.

U postupku učenja minimalizira se kriterijska funkcija:

Learning of the neural network, in the estimation process, is achieved through the supervised learning method, where the neural network is learned by the application of input values $\boldsymbol{u}(t)$ measured in the real system. Monitoring of learning process could be achieved by using the value $\boldsymbol{y}_{\mathrm{m}}(t)$ which is also obtained by measurements on the real system.

In the process of learning the criterion function is minimized:

$$E(t) = \frac{1}{2}\left[y_{\mathrm{m}}(t) - y(t) \right]^{\mathrm{T}} \left[y_{\mathrm{m}}(t) - y(t) \right] , \quad (15)$$

gdje je $E(t)$ kvadrat pogreške izlaza neuronske mreže.

Pogreška predstavlja razliku mjerenog $\boldsymbol{y}_{\mathrm{m}}(t)$ i izlaznog $\boldsymbol{y}(t)$ signala neuronske mreže. Gradijentne kriterijske funkcije u odnosu na težinske koeficijente je:

where $E(t)$ is the neural network output error squared.

The error represents the difference of the measured $\boldsymbol{y}_{\mathrm{m}}(t)$ and of the output $\boldsymbol{y}(t)$ neural network signal. Gradient criterion functions in relation to the weight coefficient are:

$$\nabla E(t) = \frac{\partial E}{\partial W^{i}} = \frac{\mathrm{d}\, y^{i}(t)}{\mathrm{d} W^{i}} \left[y_{\mathrm{m}}(t) - y(t) \right] . \quad (16)$$

U (16) vidljivo je da gradijentni postupci učenja zahtijevaju određivanje parcijalne derivacije izlaza po težinskim koeficijentima $\frac{\mathrm{d}\, y^{i}(t)}{\mathrm{d} W^{i}}$.

Gradijentna funkcija greške izlaza u ovisnosti o težinskim koeficijentima za dinamičke neuronske mreže može se odrediti na dva načina. Prvi način je povratnim prolazom u vremenu (engl. *Backpropagation Through Time* BPTT), a drugi rekurzijskim postupkom u stvarnom vremenu (engl. *Real-time recurrent learning* RTRL). Oba postupka uvažavaju utjecaj povratnog djelovanja u skrivenom sloju.

U ovom radu primijenjen je RTRL postupak određivanja gradijenta greške izlaza. Za dinamičku neuronsku mrežu na slici 2 gradijent signala izlaza u odnosu na težinske koeficijente neuronske mreže određuje se deriviranjem izlaza iz neuronske mreže $\boldsymbol{y}(t)$ po težinskim koeficjentima $\boldsymbol{W}$ koji su grupirani u matricu $\boldsymbol{W}^{1i}$ (skriveni sloj) i matricu $\boldsymbol{W}^{2i}$ (izlazni sloj).

(16) shows that the gradient learning processes require a determination of partial derivation of the exit according to weight coefficients $\frac{\mathrm{d}\, y^{i}(t)}{\mathrm{d} W^{i}}$.

The gradient output error function depending on weight coefficients for the dynamic neural network can be calculated in two ways. The first way is by backpropagation through time (BPTT), and the second is by real-time recurrent learning (RTRL). Both methods take into consideration the impact of the recurrent activity in the hidden layer.

In this work, the RTRL process for determining the gradient output error has been applied. For the dynamic neural network in figure 2, the gradient of the output signal in relation to the neural network weight coefficients is determined by derivation of the output from the neural network $\boldsymbol{y}(t)$ according to weight coefficients $\boldsymbol{W}$ which are grouped in the matrix $\boldsymbol{W}^{1i}$ (hidden layer) and the matrix $\boldsymbol{W}^{2i}$ (output layer).

Parcijalna derivacija po težinskim koeficijentima izlaznog sloja je:

Partial derivation according to the output layer weight coefficients is:

$$\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}^{2i}}=\begin{bmatrix}\left[\boldsymbol{h}^{i}(t)^{\mathrm{T}}1\right] & 0 & 0\\ 0 & . & 0\\ 0 & 0 & \left[\boldsymbol{h}^{i}(t)^{\mathrm{T}}1\right]\end{bmatrix}. \tag{17}$$

Parcijalna derivacija izlaza po težinskim koeficijentima skrivenog sloja je:

Partial output derivation according to the hidden layer weight coefficients is:

$$\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}^{1i}}=\boldsymbol{W}^{2i}\frac{\mathrm{d}\,\boldsymbol{h}^{i}(t)}{\mathrm{d}\boldsymbol{W}^{1i}} . \tag{18}$$

Derivacija izlaza skrivenog sloja po težinskim koeficijentima je:

Derivation of the hidden layer output according to weight coefficients is:

$$\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}^{1i}}=\begin{bmatrix}1-\left[\boldsymbol{h}^{1}(t)\right]^{2} & 0 & 0\\ 0 & . & .\\ 0 & . & 1-\left[\boldsymbol{h}^{N_{\mathrm{h}}}(t)\right]^{2}\end{bmatrix}\left(\begin{bmatrix}\left[\boldsymbol{u}(t)^{\mathrm{T}}\boldsymbol{h}(t-1)^{\mathrm{T}}1\right] & . & 0\\ 0 & . & .\\ 0 & . & \left[\boldsymbol{u}(t)^{\mathrm{T}}\boldsymbol{h}(t-1)^{\mathrm{T}}1\right]\end{bmatrix}+\boldsymbol{W}_{\mathrm{R}}^{1i}\frac{\mathrm{d}\,\boldsymbol{h}^{i}(t-1)}{\mathrm{d}\boldsymbol{W}^{1i}}\right) , \tag{19}$$

gdje je:

N_{h} – broj neurona u skrivenom sloju, a
$\boldsymbol{W}_{\mathrm{R}}^{1i}$ – je kvadratna matrica težinskih koeficijenata skrivenog sloja.

U matricu $\boldsymbol{W}_{\mathrm{R}}^{1i}$ izdvajaju se samo stupci matrice $\boldsymbol{W}^{1i}$ koji uključuju povratno djelovanje izlaza na ulaz skrivenog sloja.

Postupak određivanja gradijenta izlaza neuronske mreže dan je u matričnom obliku što omogućuje jednostavno proširenje i primjenu na neuronske mreže s više skrivenih slojeva koji imaju povratno djelovanje.

Najjednostavniji način učenja neuronskih mreža ostvaruje se metodom najbržeg spusta. Prirast težinskih koeficijenata tada se određuje prema:

where:

N_{h} – a number of neurons in the hidden layer, and
$\boldsymbol{W}_{\mathrm{R}}^{1i}$ – is the squared matrix of hidden layer weight coefficients.

Only the matrix columns $\boldsymbol{W}^{1i}$, which include reversible operation of the output on the hidden layer input, are allocated to the matrix $\boldsymbol{W}_{\mathrm{R}}^{1i}$.

The procedure of the neural network output gradient determination is given in the matrix form, which allows easy expansion and application to neural networks with more hidden layers with reversible effect.

The simplest way of learning neural network is realized with the method of quickest descent. Increment of weight coefficients are then determined by:

$$\boldsymbol{W}(t)=\boldsymbol{W}(t)-\beta\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}(t)}\left[\boldsymbol{y}(t)-\boldsymbol{y}_{\mathrm{est}}(t)\right] , \tag{20}$$

gdje koeficijent β određuje brzinu učenja i treba biti manji od jedan.

Metodu najbržeg spusta karakterizira spora i nesigurna konvergencija.

where the coefficient β determines the speed of learning and should be less than one.

The method of the quickest dive is characterized by slow and uncertain convergence.

Učenje dinamičkih neuronskih mreža može se znatno poboljšati metodom Proširenog Kalmanovog filtra (engl. *Extended Kalman filter*), koja je primijenjena u ovom radu. Primjena Proširenog Kalmanovog filtra osigurava bržu i stabilniju konvergenciju i manju grešku izlaza, a nedostatak ove metode je složeniji algoritam i numerički zahtjevniji postupak.

Postupak učenja neuronskih mreža Proširenim Kalmanovim filtrom dan sa:

Learning dynamic neural networks can be significantly improved by using the Extended Kalman filter which is applied in this work. Application of the Extended Kalman filter provides faster and more stable convergence and smaller output error, and a disadvantage of this method is a more complex algorithm and a numerically demanding process.

Neural network learning process with the Extended Kalman filter given with:

$$\boldsymbol{A}(t) = \mathrm{inv}\left[\eta^{-1}(t)\cdot\boldsymbol{I} + \left(\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}(t)}\right)^{\mathrm{T}}\boldsymbol{P}(t)\cdot\left(\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}(t)}\right)\right], \tag{21}$$

$$K(t) = \boldsymbol{P}(t)\left[\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}(t)}\right]\boldsymbol{A}(t)\ , \tag{22}$$

$$\boldsymbol{W}(t) = \boldsymbol{W}(t) + K(t)\cdot\left[\boldsymbol{y}_{\mathrm{m}}(t) - \boldsymbol{y}(t)\right], \tag{23}$$

$$\boldsymbol{P}(t+1) = \boldsymbol{P}(t) - K(t)\cdot\left[\frac{\mathrm{d}\,\boldsymbol{y}(t)}{\mathrm{d}\boldsymbol{W}(t)}\right]^{\mathrm{T}}\boldsymbol{P}(t) + \boldsymbol{Q}(t)\ . \tag{24}$$

U (21) prvi član $\eta^{-1}(t)\cdot I$ je kvadratna dijagonalna matrica u kojoj je η stopa učenja (engl. *scalar learning rate*), a drugi član je skalarni umnožak matrice gradijenata $\left[\frac{\mathrm{d}\,y(t)}{\mathrm{d}W(t)}\right]$ normiran s matricom kovarijanci $P(t)$. Vrijednost stope učenja η se programirano mijenja tijekom učenja od 10^6 na početku do 1 na kraju učenja. Vrijednost druge matrice mijenja se u ovisnosti o učenju, tako što se iznos elemenata matrice gradijenata smanjuje kako učenje neuronske mreže napreduje.

Kalmanovo pojačanje $K(t)$ u (22) određuje se kao umnožak matrice kovarijanci $P(t)$, matrice gradijenata $H(t)$ i matrice $A(t)$. Normiranjem iznosa Kalmanovog pojačanja K, matricom $A(t)$ nadzire se brzina učenja.

Prirast težinskih koeficjenata u (23) određuje se kao umnožak Kalmanovog pojačanja i pogreške izlaza neuronske mreže. Normiranjem iznosa prirasta težinskih koeficijenata s matricom $A(t)$ koja se izračunava u svakom koraku, postiže se povratno djelovanje koje proces učenja u početku usporava i usmjerava ka sigurnijoj konvergenciji, a u završnoj fazi učenja rezultira brzom konvergencijom i velikom smanjenju iznosa kvadrata pogreške $E(t)$ u kriterijskoj funkcije (15).

U (24) određuje se nova korekcijska vrijednost matrice kovarijanci $P(t+1)$ koja se koristi u sljedećem koraku učenja. Početna vrijednost matri-

In (21) the first member $\eta^{-1}(t)\cdot I$ is the squared diagonal matrix in which η is the learning rate (engl. *scalar learning rate*), and the second member is the scalar product of matrix gradients $\left[\frac{\mathrm{d}\,y(t)}{\mathrm{d}W(t)}\right]$ standardized by the covariance matrix $P(t)$. During the learning, the learning rate value η changes according to a program from 10^6 at the beginning to 1 at the end of the learning. The value of the second matrix changes depending on the learning, so that the amount of the matrix gradients reduces as the learning of the neural networks progresses.

The Kalman's amplification $K(t)$ in (22) is defined as the multiplication of the covariance matrix $P(t)$, the gradient matrix $H(t)$ and the matrix $A(t)$. Standardization of the amount of Kalman's amplification K, the speed of learning is monitored by virtue of the matrix $A(t)$.

The increment of weight coefficients in (23) is defined as the product of Kalman's amplification and the neural network output error. The standardization of the increment of weight coefficients by the matrix $A(t)$ which is calculated at each step, reversible operation is achieved which at first slows down the learning process and directs to a more secure convergence, and at the final stage of the learning, results in fast convergence and a significant reduction of the squared error amount $E(t)$ in criteria function (15).

ce $P(t)$ uzima se kao kvadratna dijagonalna matrica gdje je vrijednost koeficijenata na glavnoj dijagonali $\geq 10^3$. Matrica $Q(t)$ je kvadratna dijagonalna matrica u kojoj se vrijednost elemenata na glavnoj dijagonali programirano smanjiva od 0,5 na početku učenja do 10^{-6} na kraju učenja. Matricom $Q(t)$ unosi se šum u postupak učenja što omogućava izlazak iz lokalnih minimuma gradijentne funkcije i povoljno utječe na konvergentnost postupka.

Postupak učenja dinamičkih neuronskih mreža proširenim Kalmanovim filtrom veoma je učinkovit zbog prediktor-korektor načina određivanja prirasta težinskih koeficijenata i korekcije tog prirasta s matricom $A(t)$ koja se određuje na prije opisani način.

3 REZULTATI ESTIMACIJE PRIMJENOM DINAMIČKIH NEURONSKIH MREŽA

Učenje dinamičkih neuronskih mreža za estimaciju kuta opterećenja provedeno je na laboratorijskom modelu sinkronog generatora nazivne snage 80 kVA. Ulazne veličine u estimacijski model, temeljem provedenih istraživanja [8], odabrane su heurističkim pristupom. Za učenje neuronskih mreža odabiru se standardno mjerljive veličine koje se dovode na ulaze mreže: napon generatora U_G(t), struja uzbude I_{fd}(t), djelatna P_G(t), jalova Q_G(t) snaga generatora, prethodno stanje napona generatora $U_G(t-1)$ i prethodno stanje struje uzbude $I_{fd}(t-1)$, kako je prikazano na slici 1. Navedene veličine formiraju ulazni vektor u dinamičku neuronsku mrežu:

(24) determines a new correction value of the covariance matrix $P(t+1)$ which is used in the next step of the learning. The initial matrix value $P(t)$ is taken as a squared diagonal matrix where the value of coefficients is on the main diagonal $\geq 10^3$. The matrix $Q(t)$ is a squared diagonal matrix in which the value of the elements on the main diagonal reduces according to a programme from 0,5 at the beginning of the learning to 10^{-6} at the end of the learning. The matrix $Q(t)$ introduces noise in the process of learning, which allows exit from the gradient function local minimums, and favourably affects the convergence of the process.

The process of dynamic neural networks learning expanded with Kalman's filter is very effective because the predictor-corrector method to determine the increment of weight coefficients and correction of that increment with the matrix $A(t)$ which is determined in the manner described above.

3 ESTIMATION RESULTS BY APPLICATION OF DYNAMIC NEURAL NETWORKS

The learning of dynamic neural networks for load angle estimation is conducted on a laboratory model of a synchronous generator with 80 kVA nominal power. Estimation model input values, based on conducted research [8], were selected by heuristic approach. For the neural networks learning standard measurable values brought on network inputs were chosen: generator voltage U_G (t), excitation current I_{fd}(t), active P_G (t), reactive Q_G (t) generator power, the previous generator voltage state $U_G(t-1)$ and the previous state of excitation current $I_{fd}(t-1)$, as shown in figure 1. The specified values form the input vector in the dynamic neural network:

$$\boldsymbol{u}(t) = \left[U_G(t) \cdot U_G(t-1) \cdot I_{fd}(t) \cdot I_{fd}(t-1) \cdot P_G(t) \cdot Q_G(t)\right]^T, \quad (25)$$

dok je kut opterećenja $\delta_{est}(t)$ izlaz neuronske mreže $\boldsymbol{y}_m(t)$:

while the load angle $\delta_{est}(t)$ is the output of the neural network $\boldsymbol{y}_m(t)$:

$$\boldsymbol{y}_m(t) = \delta_{est}(t) \ . \quad (26)$$

Ulazne veličine u neuronsku mrežu dobivene su mjerenjem električnih veličina koje se koriste za potrebe vođenja pogona sinkronog generatora i regulaciju sustava uzbude sinkronog generatora. Trenutačne vrijednosti napona generatora i struje uzbude dobivene su izravnim mjerenjem

Input neural network values are obtained by measuring electrical values that are used for the purpose of synchronous generator operation and synchronous generator excitation system. The present values of the generator voltage and excitation current are obtained by direct measurement with a sampling fres frekvencijom uzorkovanja od 1 000 Hz, dok se stacionarne vrijednosti djelatne i jalove snage generatora dobivaju iz mjernih pretvornika.

Estimacija kuta opterećenja provedena je pri različitim pogonskim režimima rada sinkronog generatora na krutoj mreži. Na početku je skokovito mijenjan referentni napon generatora uz konstantnu mehaničku snagu pogonskog stroja, dok je u nastavku estimacijski postupak proveden uz kontinuiranu promjenu mehaničke snage i skokovitu promjenu referentnog napona sinkronog generatora.

Na slici 3 pokazani su rezultati estimacije kuta opterećenja pri skovitoj promjeni referentnog napona generatora uz konstantnu mehaničku snagu pogonskog stroja. Referentni napon postavljen je na iznos od 0,8 pu. Stacionarnom iznosu referentnog napona superponirana je pulsna promjena od −0,2 pu s frekvencijom od 0,1 Hz.

Promjena referentnog napona rezultirala je promjenom ulaznih veličina u neuronsku mrežu, kao što je prikazano na slici 3 pod a. Na slici 3 pod b usporedno su prikazani rezultati estimirane vrijednosti kuta opterećenja (δ_{est}) primjenom dinamičkih neuronskih mreža i rezultati dobiveni mjerenjem (δ). Na slici 3 pod c pokazana je razlika izmjerenog i estimiranog kuta opterećenja ($\delta - \delta_{est}$). Srednja apsolutna pogreška estimiranog kuta opterećenja pokazanog na slici 3 iznosi 0,38 °el., pogreška stacionarnog stanja je veoma malena i iznosi oko 0,5 °el., a maksimalno odstupanje iznosi 1,64 °el. Na temelju dobivenih rezultata vidljivo je praktički potpuno slaganje izmjerenog i estimiranog kuta opterećenja. Razlika između izmjerenog i estimiranog kuta opterećenja posljedica je postojanja mjernog šuma.

Kako bi se pokazala valjanost razvijenog estimacijskog modela zasnovanog na dinamičkoj neuronskoj mreži provedena je estimacija kuta opterećenja uz kontiranu promjenu mehaničke snage pogonskog stroja i pulsnu promjenu referentnog napona. U prvom slučaju odabrana je vrijednost referentnog napona generatora od 1,0 pu, a postupak estimacije proveden je pri pulsnoj promjeni od − 0,2 pu kako je pokazano na slici 4. U drugom slučaju je promijenjena radna točka generatora tako da se išlo sa sniženim naponom generatora, što se postiglo postavljanjem referentnog napona na vrijednost od 0,85 pu. Postupak estimacije proveden je, kao i u prvom slučaju, pri pulsnoj promjeni od − 0,2 pu što je pokazano na slici 5.

Rezultati estimacijskog postupka dobiveni primjenom dinamičke neuronske mreže, za odabrana dva slučaja prikazani su na slikama 4 i 5 i to: estimirane (δ_{est}) i izmjerene (δ) vrijednosti kuta opterećenja, također i razlike između ove dvije veličine ($\delta - \delta_{est}$).

quency of 1 000 Hz, while the fixed values of active and reactive generator power are obtained from the measurement converter.

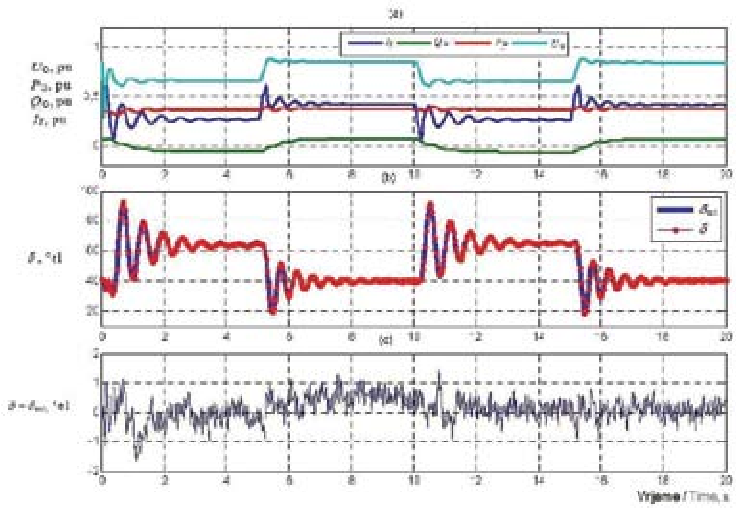
Load angle estimation was conducted at different operating modes of the synchronous generator on a rigid network. At the beginning, the reference generator voltage precipitately changed at a constant mechanical engine force, while the following estimation process was conducted at a continuous change of mechanical power and a precipitate change of the synchronous generator reference voltage.

Figure 3 displays the results of load angle estimation at a precipitate change of the generator reference voltage with a constant mechanical engine force. The reference voltage is set at the amount of 0,8 pu. An impulse change from −0,2 pu with a 0,1 Hz frequency is superposed to the stationary reference voltage.

Change of the reference voltage resulted in the change of neural network input values, as shown in figure 3 under a. In figure 3 under b parallel results are shown of the estimated load angle value (δ_{est}) using dynamic neural networks and results obtained by measurement (δ). In figure 3 under c the difference is shown bewteen the measured and the estimated load angle ($\delta - \delta_{est}$). Average estimated load angle absolute error shown in figure 3 is 0,38 °el., stationary error is very small in the amount of about 0,5 °el., and the maximum deviation is 1,64 °el. The obtained results show almost complete compliance of the measured and the estimated load angle. The difference between the measured and the estimated load angle is a consequence of the measurement noise.

In order to show the validity of the developed estimation model based on the dynamic neural network load angle estimation is conducted with continuous change of the mechanical engine power and reference voltage impulse change. In the first case the generator reference voltage value of 1,0 pu was selected, and the estimation method was conducted at the impulse change of − 0,2 pu as shown in figure 4. In the second case, the operating point of the generator was changed by means of lower generator voltage, which was achieved by setting of the reference voltage value to 0,85 pu. The estimation method was conducted, just as in the first case, at the impulse change of − 0,2 pu which is shown in figure 5.

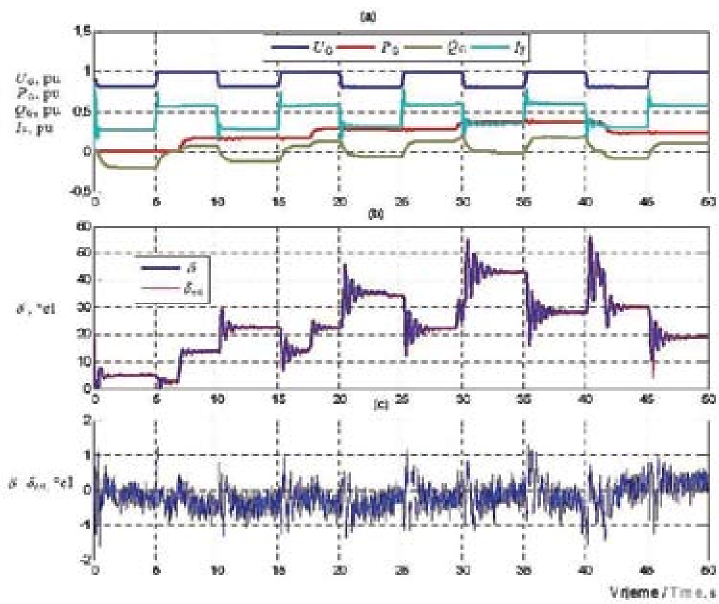
The results of the estimation method obtained by using the dynamic neural network are shown, for the selected two cases, in figures 4 and 5 as follows: the estimated (δ_{est}) and the measured (δ) load angle values, and also the differences between these two values ($\delta - \delta_{est}$).



a) ulazne veličine u neuronsku mrežu / neural network input values: napon generatora / generator voltage (U_G), djelatna snaga / active power (P_G), jalova snaga / reactive power (Q_G) i / and struja uzbude / excitation current (I_{fd}),
b) usporedni prikaz izmjerenog (δ) i estimiranog (δ_{est}) kuta opterećenja / comparative display of the measured and estimated (δ_{est}) load angle,
c) razlika ($\delta - \delta_{est}$) izmjerenog (δ) i estimiranog (δ_{est}) kuta opterećenja / the difference ($\delta - \delta_{est}$) between the measured (δ) and estimated (δ_{est}) load angle.

Slika 3 — Rezultati estimacijskog postupka provedenog pri nazivnom naponu od 0,85 pu pulsnoj promjeni referentnog napona od − 0,2 pu i stalnoj mehaničkoj snazi

Figure 3 — Results of the estimated method conducted at the nominal voltage of 0,85 pu impulse change of the reference voltage of − 0,2 pu and ongoing mechanical power



a) ulazne veličine u neuronsku mrežu / neural network input values : napon generatora / generator voltage (U_G), djelatna snaga / active power (P_G), jalova snaga / reactive power (Q_G) i / and struja uzbude / excitation current (I_{fd})
b) usporedni prikaz izmjerenog (δ) i estimiranog (δ_{est}) kuta opterećenja / comparative display of the measured (δ) and the estimated (δ_{est}) load angle,
c) razlika ($\delta - \delta_{est}$) izmjerenog (δ) i estimiranog (δ_{est}) kuta opterećenja / the difference ($\delta - \delta_{est}$) between the measured (δ) and the estimated (δ_{est}) load angle.

Slika 4 — Rezultati estimacijskog postupka provedenog pri nazivnom naponu od 1,0 pu pulsnoj promjeni referentnog napona od − 0,2 pu i kontinuiranoj promjeni mehaničke snage

Figure 4 — Results of the estimation method conducted at the nominal voltage of 1,0 pu, impulse change of reference voltage − 0,2 pu and constant change of mechanical power

Kako je pokazano na slikama 4 i 5, rezultati dobiveni primjenom dinamičke neuronske mreže, pokazuju dobro slaganje između izmjerene i estimirane vrijednosti kuta opterećenja. Vidljivo je dobro slaganje rezultata i pri poremećajima u pogonu – dinamici, također i u ustaljenom stanju.

Točnost estimacijskog postupka procijenjena je na osnovi razlike izmjerenog i estimiranog kuta opterećenja $(\delta - \delta_{est})$.

U prvom slučaju kada je referentni napon generatora 1,0 pu (slika 4), maksimalna pogreška iznosi 1,67 °el., srednja apsolutna pogreška iznosi 0,37 °el., a pogreška u stacionarnom stanju manja je od srednje apsolutne pogreške. Slični rezulata postignuti su i u sljedećem pokusu sa sniženim iznosom referentnog napona generatora od 0,85 pu (slika 5) gdje maksimalna pogreška iznosi 2,67 °el., srednja apsolutna pogreška iznosi 0,53 °el., a pogreška u stacionarnom stanju je manja od srednje apsolutne greške.

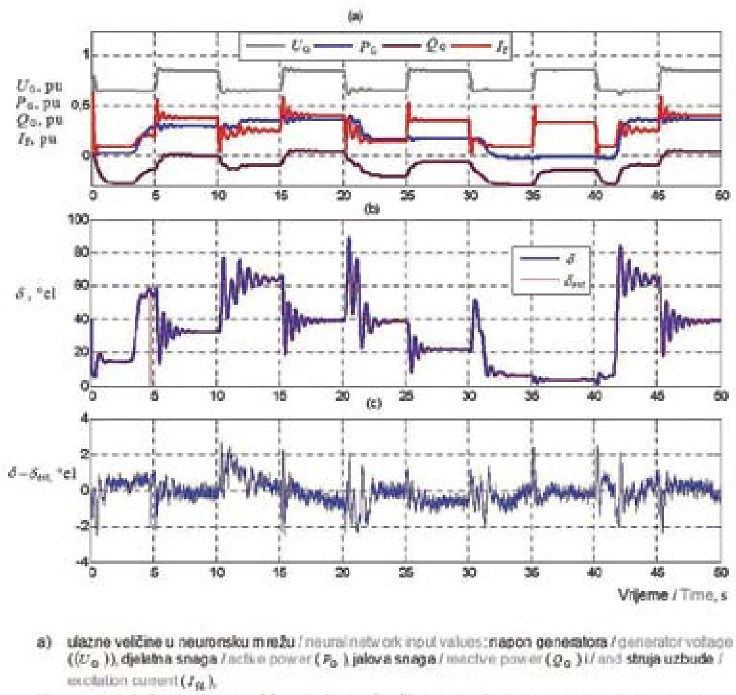
Temeljem dobivenih rezultata može se zaključiti na mogućnost primjene dinamičkih neuronskih mreža za estimaciju kuta opterećenja u čitavom području rada sinkronog generatora, definiranim

As shown in figures 4 and 5, the results obtained by using the dynamic neural network show good compliance between the measured and the estimated load angle value. Good compliance of the results is shown even at malfunction – the dynamics, as well as at steady state.

Accuracy of the estimation process is estimated on the basis of the measured and the estimated load angle differences $(\delta - \delta_{est})$.

In the first case, when the reference generator voltage is 1,0 pu (figure 4), the maximum error is 1,67 °el., average absolute error is 0,37 °el., and the stationary state error is less than average absolute error. Similar results have been achieved in the next experiment with the smaller amount of reference generator voltage of 0,85 pu (figure 5) where the maximum error is 2,67 °el., average absolute error is 0,53 °el., and stationary state error is less than the average absolute error.

Based on the obtained results, it can be concluded that it is possible to use dynamic neural networks for load angle estimation in the entire synchronous generator operation area, defined by the operation map. It is necessary to emphasize that the



a) ulazne veličine u neuronsku mrežu / neural network input values: napon generatora / generator voltage (U_G), djelatna snaga / active power (P_G), jalova snaga / reactive power (Q_G) i / and struja uzbude / excitation current (I_{fd}),
b) usporedni prikaz izmjerenog (δ) i estimiranog (δ_{est}) kuta opterećenja / comparative display of the measured (δ) and the estimated (δ_{est}) load angle,
c) razlika ($\delta - \delta_{est}$) izmjerenog (δ) i estimiranog (δ_{est}) kuta opterećenja / the difference ($\delta - \delta_{est}$) between the measured (δ) and the estimated (δ_{est}) load angle.

Slika 5 — Rezultati estimacijskog postupka provedenog pri nazivnom naponu od 0,85 pu, pulsnoj promjeni referentnog napona od − 0,2 pu i kontinuiranoj promjeni mehaničke snage

Figure 5 — Results of the estimation method conducted at the nominal voltage of 0,85 pu, impulse change of the reference voltage − 0,2 pu and continuous change of mechanical power

pogonskom kartom. Potrebno je naglasiti da se dinamička neuronska mreža uči s pogonskim veličinama koje su dobivene on-line mjerenjem u realnim pogonskim uvjetima, što uključuje i mjerenje radne i jalove snage generatora.

U ovom radu, rezultati dobiveni primjenom dinamčke neuronske mreže u postupku estimacija kuta opterećenja pokazuju dobro slaganje izmjerenih i estimiranih vrijednosti kuta opterećenja temeljem čega se može zaključiti da ograničenja u on-line mjerenju snaga nemaju značajnijeg utjecaja na točnost estimacije.

Dobiveni rezultati pokazuju da se primjenom dinamičke neuronske mreže postiže visoka točnost u postupku estimacije kuta opterećenja. Estimirana vrijednost kuta opterećenja može se upotrijebiti za proširenje funkcija regulatora sustava uzbude sinkronog generatora bez uvođenja dodatnih mjerenja. Signal kuta opterećenja može se upotrijebiti za realizaciju stabilizatora EES-a, također i za realizaciju zaštite u kapacitivnom području rada sinkronog generatora, kada se želi postići rad u području ekstremno niskih struja uzbude, praktički na teorijskoj granici stabilnog rada.

4 ZAKLJUČAK

U radu je pokazana mogućnost primjene dinamičkih neuronskih mreža u postupku estimacije kuta opterećenja sinkronog generatora u radu na elektroenergetski sustav. Istražen je i definiran izbor ulaznih veličina i struktura dinamičke neuronske mreže. Za učenje dinamičke neuronske mreže koristi se podaci iz odziva pogonskih veličina snimljenih u ustaljenom pogonskom stanju i pri poremećajima u radu sinkronog generatora na mrežu. Učenje je provedeno primjenom metode Kalmanovog filtra.

Temeljem dobivenih rezultata može se zaključiti da se primjenom dinamičkih neuronskih mreža postiže visoka točnost u postupku estimacije kuta opterećenja.

Učenje dinamičke neuronske mreže provodi se jednokratno na računalu, dakle ne opterećuje procesorski sustav regulatora sustava uzbude. Tako naučena mreža može se implementirati u digitalizirani regulator sustava uzbude kao jednostavno softversko proširenje. Podatak o kutu opterećenja sinkronog generatora u radu na elektroenergetski sustav dobiven primjenom estimacijkog postupka zasnovanog na dinamičkim neuronskim mrežama može se primijeniti u realizaciji dodatnih funkcija regulatora sustava uzbude pri čemu dodatna mjerenja nisu potrebna.

dynamic neural network is learned by the operation values which are obtained by virtue of on-line measurement in real operating conditions, which includes measuring of active and reactive generator power.

In this paper, the results obtained by using the dynamic neural network in the process of the load angle estimation show good compliance of the measured and the estimated load angle values based on which it can be concluded that the restrictions in on-line power measurement do not have significant impact on the accuracy of estimation.

The obtained results show that the use of the dynamic neural network achieves high accuracy in the load angle estimation method. The estimated value of the load angle can be used for expanding the regulation functions of the synchronous generator excitation system without additional measurements. The load angle signal can be used for the implementation of the PPS stabilizer and also for the realization of protection in the capacitive area of the synchronous generator operation, when operation is desired in the area with extremely low-current excitation, practically at the theoretical border of stable operation.

4 CONCLUSION

This paper shows the possibility of using a dynamic neural network in the process of synchronous generator operation load angle estimation on the power system. The choice of input values and the structure of the dynamic neural network is explored and defined. For the learning of the dynamic neural network data is used from the response of operational values recorded in standard operating condition and at malfunction in the synchronous generator operation to the network. The learning is carried out by using the Kalman's filter method.

Based on the obtained results it can be concluded that the application of the dynamic neural network achieves high accuracy in the process of load angle estimation.

The learning of the dynamic neural network is carried out one-time through the computer, so that it does not burden the processor system of the system excitation regulator. The network learned in such way can be introduced into the digitized excitation system regulator as simple software extension. The data on the synchronous generator load angle in operation on the power system obtained by virtue of the estimation method based on dynamic neural networks can be applied in the realization of additional excitation system regulator functions whereat additional measurements are not necessary.

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ODRŽAVANJE NAZIVNIH PERFORMANSI PLINSKE TURBINE PRI POVIŠENIM TEMPERATURAMA OKOLIŠA

MAINTAINING DECLARED PERFORMANCE IN GAS TURBINES DURING INCREASED AMBIENT TEMPERATURES

Marin Begović, Zagreb, Hrvatska

Klasični proces plinske turbine karakterizira kompresija zraka iz okoline, koji se u komorama izgaranja zagrijava izgaranjem goriva te tako stvoreni dimni plinovi ekspandiraju u turbini i proizvode mehanički rad. Performanse plinske turbine ovise o svemu što mijenja gustoću i/ili maseni protok zraka na usisu kompresora. Najočitije promjene u performansama plinske turbine su smanjenje snage i povećanje specifične potrošnje goriva s porastom temperature okoliša, pri čemu nastaju značajna odstupanja od vrijednosti garantiranih (i postignutih) pri ISO uvjetima. Hlađenjem zraka na usisu kompresora pri povišenim temperaturama okoliša postiže se povećanje masenog protoka i kompresijskog omjera, te se sprječava smanjenje snage i povećanje specifične potrošnje goriva. Primjenom plinskih turbina u kombikogeneracijskim postrojenjima za proizvodnju električne i toplinske energije, povećanje masenog protoka kroz plinsku turbinu dovodi do povećanja energije koju dimni plinovi odvode na ispuhu turbine, a koja se kod kombi postrojenja u kotlu utilizatoru predaje ciklusu parne turbine. Time je kod kombi postrojenja efekt smanjenja specifične potrošnje goriva još značajniji. U radu je na primjeru turbine GE-PG6101FA prikazana ovisnost o okolišnim klimatskim uvjetima, te način na koji se ta ovisnost može smanjiti ili otkloniti.

The classical gas turbine process is characterised by air compression from its surroundings, heating fuel in the combustion chambers, hence causing the created flue gases to expand in the turbine and thus induce mechanical action. The performance of gas turbine depends on anything that affects the airflow density and/or mass at the compressor inlet. The most obvious changes in gas turbine performance is a reduction in power and an increase in specific fuel consumption following an increase in the ambient temperature, resulting in significant deviations of the guaranteed (and achieved) values at ISO conditions. In cooling air at the compressor inlet at increased ambient temperatures, an increase in the mass flow and compression ratio is achieved, thus preventing a reduction in power and an increase in specific fuel consumption. When using gas turbines in combined cycle cogeneration power plants for the production of electrical and thermal power, increasing mass flow through gas turbines leads to an increase in power transferred by the flue gases to the turbine exhaust, and which in the waste heat recovery boiler at the combined cycle plant transfers to the steam turbine cycle. Consequently, the effect at the combined cycle plant is a more significant reduction in specific fuel consumption. The work has used the example of the GE-PG610FA turbine to show the dependency on surrounding climatic conditions, and the manner in which this dependency can be reduced or removed.

Ključne riječi: hlađenje zraka na usisu plinske turbine; izlazna snaga; plinska turbina; specifična potrošnja goriva

Key words: cooling air at the gas turbine inlet, output power, gas turbine, specific fuel consumption

1 UVOD

Plinske turbine su vrlo pouzdani, raspoloživi i učinkoviti strojevi, čija je uloga pogonskog stroja našla široku primjenu u postrojenjima za proizvodnju električne i toplinske energije, te u industriji. Rasprostranjenost u primjeni potiče njihov razvoj u smjeru postizanja maksimalne efikasnosti i minimiziranja pogonskih troškova. Razvoj plinskih turbina radi poboljšanja efikasnosti provodi se u dva osnovna područja:

- konstrukcijska unaprjeđenja plinskih turbina kojima se omogućuje rad sa sve višim temperaturama na ulazu u prvi stupanj turbine, višestupanjske kompresije s međuhlađenjem, te višestupanjske ekspanzije s međuzagrijavanjem i regeneracijom topline dimnih plinova koji se primjenjuju u razvoju i unaprjeđenju novih modela turbina, a odnose se prvenstveno na poboljšanje osnovnog toplinskog procesa koji se odvija u turbini, i
- smanjenje utjecaja uvjeta eksploatacije na rad turbine, pri čemu se nastoji poboljšati efikasnost i smanjiti degradacija snage prouzročena utjecajem okolišne temperature, vlage, čistoće zraka na ulazu kompresora, starosti postrojenja i sličnog.

Po svojoj konstrukciji plinske turbine su strojevi konstantnog radnog volumena, a njihova je izlazna snaga proporcionalna masenom protoku radnog medija, tj. zraka kojeg iz okoliša dobavlja kompresor. Pri povišenim temperaturama okolišnog zraka, plinske turbine gube snagu zbog konstantnog volumnog ali smanjenog masenog protoka zraka, koji je povećanjem temperature sve rjeđi i čiji se specifični volumen u tom slučaju povećava.
Premda su plinske turbine vrlo pouzdani i široko primijenjeni strojevi u proizvodnji električne energije, njihova slaba točka je ovisnost o svemu što mijenja gustoću i/ili maseni protok zraka na usisu kompresora, tj. ovisnost o realnim atmosferskim uvjetima u kojima se nalaze tijekom eksploatacije.

Smanjenjem masenog protoka zraka ne samo da se smanjuje izlazna snaga plinske turbine, nego se smanjuje i količina dimnih plinova čija se energija u kotlu utilizatoru predaje ciklusu parne turbine. Smanjenjem energije predane u utilizatoru, smanjuje se i učinkovitost ciklusa parnoturbinskog postrojenja, bez obzira da li je ono u kondenzacijskom, toplifikacijskom ili mješovitom toplifikacijsko-kondenzacijskom režimu rada. Prema tome, degradacija snage plinske turbine uzrokuje degradaciju snage ostalih vezanih jedinica.

Iako efekt smanjenog masenog protoka zraka prati i smanjena potrošnja goriva u njenom apsolutnom

1 INTRODUCTION

Gas turbines are very reliable, fairly available and efficient machines, whose role as a drive machine has found wide application in plants used for the production of electrical and thermal power, and in the industry in general. Its extensive use has encouraged development leading to the achievement of optimal efficiency and minimising operational costs. Development of gas turbines for improving efficiency is carried out in two basic fields:

- construction improvements of gas turbines allowing operation at higher temperatures upon entering the first stage of the turbine, multi-stage compression with inter-cooling, and multi-stage expansion with inter-heating and thermal regeneration of flue gas used in the development and advancement of new turbine models, relating primarily to improvements in the basic thermal process that occurs in the turbine, and
- reducing the impact of exploitation conditions on the turbine operation, while endeavouring to improve efficiency and reduce power losses caused by the effects of ambient temperature, humidity, air purity at the compressor entry, age of the plant and so on.

Based on its construction, gas turbines are machines with constant operational volume, and their output power is proportional to the mass flow of the operating medium, i.e. air from the surroundings supplied by the compressor. At higher ambient air temperatures, gas turbines lose power due to the constant volume but reduced air mass flow, which, due to an increase in temperature, is all the more sparser and the specific volume of which increases in such cases. Although gas turbines are very reliable and widely applicable machines in the production of electrical power, their weakness is a dependency on anything that changes air flow density and/or mass at the compressor inlet, i.e. dependency on actual atmospheric conditions in which they are found during exploitation.

Reducing airflow mass does not only reduce the output power of the gas turbine, but also reduces the amount of flue gases the energy of which in the waste heat recovery boiler is transferred to the steam turbine cycle. Reducing the energy transferred to the recovery boiler reduces the efficiency of the steam turbine power plant cycle, regardless of whether it is in the condensation, thermal or mixed thermal-condensation operating mode. Hence, a power reduction in a gas turbine causes a power reduction in the other related units.

Even though the effect of reduced airflow mass is followed by a reduction in fuel consumption in its iznosu, specifična potrošnja goriva (specifična potrošnja topline) se povećava proporcionalno porastu temperature zraka na ulazu u kompresor. Kod primjene plinskih turbina u kombikogeneracijskim postrojenjima za proizvodnju električne i toplinske energije povećanjem specifične potrošnje goriva negativna posljedica povećanja temperature zraka uzrokuje smanjenje iskoristivosti i ekonomičnosti rada cijelog kombikogeneracijskog bloka.

absolute value, specific fuel consumption (specific gas consumption) increases proportionally with a rise in air temperature at the compressor inlet. When using gas turbines in combined cycle cogeneration power plants for the production of electrical and thermal power, by increasing the specific fuel consumption, the resulting negative effect of an increase in air temperatures causes a reduction in utilizable and economically viable operation of the whole combined cycle cogeneration unit.

2 ODSTUPANJE KARAKTERISTIKA PLINSKIH TURBINA OD STANDARDNIH VRIJEDNOSTI

Termodinamički kružni proces po kojem plinovi proizvode rad u plinskoj turbini naziva se Braytonov ciklus, a u osnovi je to teorijski Jouleov proces otvorenog tipa. Sastoji se od dvije izobare i dvije izentrope te je prikazan na slici 1 u p-V i T-s dijagramu. Proces započinje usisom zraka iz okoliša (točka 1, slika 1). Nastavlja se komprimiranjem zraka do točke 2. Od točke 2 do točke 3 komprimiranom zraku se predaje toplina izgaranjem goriva pri konstantnom tlaku:

2 DEVIATION OF GAS TURBINE CHARACTERISTICS FROM STANDARD VALUES

The thermodynamic cyclic process whereby gases produce operation in the gas turbines is called the Brayton Cycle, and is fundamentally the theoretical open-type Joule process. It comprises of two isobars and two isentropes and is shown in Figure 1 in the u p-V and T-s diagram. The process begins with air suction from the surroundings (point 1, Figure 1). It continues with compressed air up to point 2. From point 2 to point 3, heat is transferred to compressed air by fuel combustion at a constant pressure:

$$Q_{\mathrm{dov}} = Q_{23} = mc_{\mathrm{p}}(T_3 - T_2)\ , \quad \mathrm{J/ciklusu}\ , \qquad (1)$$

gdje je:

Q_{dov} – dovedena toplina,
m – masa zraka,
c_{p} – specifična toplina zraka pri stalnom tlaku.

Proces se nastavlja izentropskom ekspanzijom od točke 3 do točke 4, te se pri tome dobiva mehanički rad od kojeg se jedan dio koristi za pogon kompresora, dok je ostalo korisni rad za pogon gonjenog stroja. Od točke 4 do 1 toplina se odvodi, što predstavlja ispuh i izlazak dimnih plinova iz turbine:

where:

Q_{dov} – incoming heat,
m – mass,
c_{p} – specific heat at constant pressure.

The process continues through isentropic expansion from point 3 to point 4, thus producing mechanical action part of which is used for compressor operation, while the remaining part is used for operation of the driven machine. Heat travels from point 4 to 1, representing the exhaust and exiting of flue gases from the turbine:

$$Q_{\mathrm{odv}} = Q_{41} = mc_{\mathrm{p}}(T_4 - T_1)\ , \quad \mathrm{J/ciklusu}\ , \qquad (2)$$

gdje je:

Q_{dov} – odvedena toplina.

Odvođenje topline ili ispuh dimnih plinova mogu biti u atmosferu, ili u slučaju kombikogeneracijskog postrojenja dimni plinovi ulaze u kotao utili-

where:

Q_{dov} – outgoing heat.

Removal of heat or outflow of flue gases may occur into the atmosphere, or, in case of a combined cycle cogeneration power plant, the flue gases en-

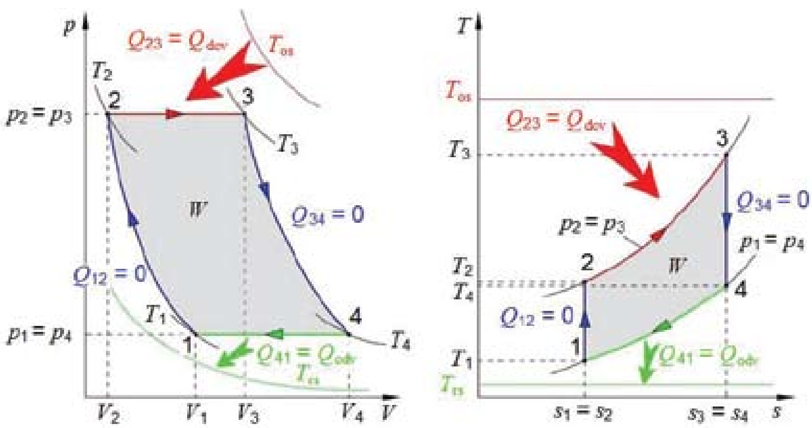
zator u kojem se toplina ispuha plinske turbine koristi za proizvodnju pare.
Dobiveni rad W po ciklusu je jednak:

ter the waste heat recovery boiler where heat from the gas turbine exhaust is used for production of steam.
Gained work W per cycle equals:

$$W = Q_{dov} - Q_{odv} \ , \ \text{J/ciklusu} \ . \qquad (3)$$

Kako atmosferski uvjeti okoliša u kojem započinje kružni proces plinske turbine (točka 1, slika 1) variraju ovisno o dobu dana, godišnjem dobu, lokaciji na kojoj je plinska turbina instalirana, nametnula se potreba određivanja standardnih uvjeta na kojima se temelje jamstvene karakteristike, a u odnosu na koje se rade i sve ostale usporedbe karakteristika postignutih izvan standardnih uvjeta. U industriji plinskih turbina standardni uvjeti zraka na ulazu u kompresor su: temperatura 15 °C, relativna vlažnost 60 %, te tlak od 1 013 mbar. Nominirani su od International Standards Organization (ISO uvjeti).

Since the surrounding atmospheric conditions in which the gas turbine cyclic process (point 1, Figure 1) begins varies depending on the time of day, season of the year, location where the gas turbine is installed, there need has arisen for determining the standard conditions upon which the guaranteed characteristics are founded, and in relation to which all other comparisons of characteristics achieved outside of the standard conditions are made. In the gas turbine industry, standard air conditions at the compressor inlet are: temperature 15 °C, relative humidity 60 %, and a pressure of 1 013 mbar. These comply with the International Standards Organisation (ISO conditions).



Slika 1 — Termodinamički teoretski proces plinske turbine prikazan u p-v i T-s dijagramu [1]
Figure 1 — Thermodynamic theoretical process for gas turbines shown in the p-v and T-s diagram [1]

U radu se za analizu koriste podaci plinske turbine General Electric tip PG 6101 FA. Performanse plinske turbine GE - PG 6101 FA temeljene na ISO standardu razlikuju se s obzirom na vrstu goriva koju turbina koristi.

Prema ISO uvjetima zraka na ulazu u kompresor i pogon na dizelsko gorivo, odnosno prirodni plin, definirane su jamstvene karakteristike na baznom opterećenju (tablica 1).

Analysis during operation uses data from the General Electric PG 6101 FA type gas turbine. Performance of the GE – PG 6101 FA gas turbine based on ISO standards differs with respect to the type of fuel used by the turbine.

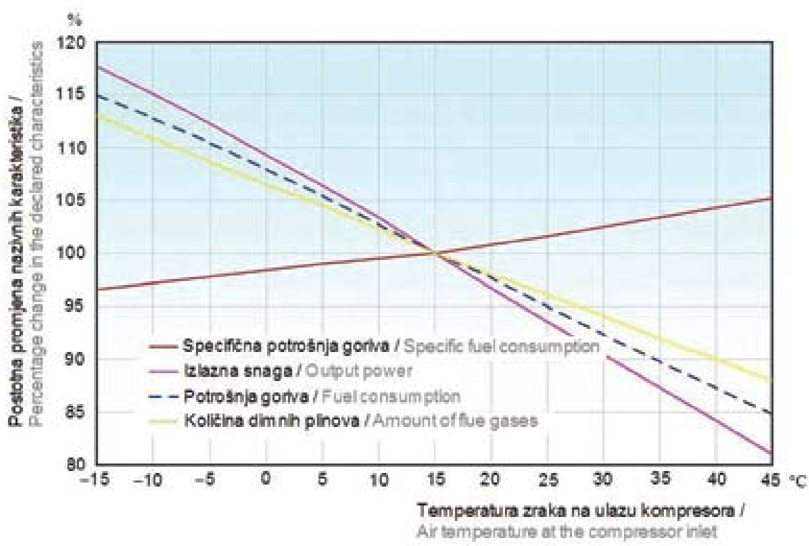
According to ISO conditions relating to air at the compressor intake and the engine running on diesel fuel or on natural gas, guaranteed characteristics are defined for base loads (Table 1).

Tablica 1 – Jamstvene karakteristike za plinsku turbinu GE - PG 6101 FA prema ISO uvjetima [2]
Table 1 – Guaranteed characteristics for the GE - PG 6101 FA gas turbine according to ISO conditions [2]

Karakteristike turbine / Turbine Characteristics	Jedinica / Measurement unit	Gorivo / Fuel	
		Dizelsko gorivo / Diesel fuel	Prirodni plin / Natural gas
Snaga na generatoru / Power at the generator	kW	74 270	69 450
Specifična potrošnja topline / Specific thermal consumption	kJ/kWh	11 152	10 593
Maseni protok dimnih plinova / Mass flow of flue gases	kg/h	761 100	731 600
Izlazna temperatura dimnih plinova / Output flue gases temperature	°C	584	596,7

Sve karakteristike plinske turbine značajno se mijenjaju promjenom atmosferskih uvjeta ulaznog zraka. Te promjene mogu biti i na dnevnoj osnovi vrlo velike, mada je njihova promjena najočitija usporedbom zimskog i ljetnog režima rada. Na slici 2 prikazana je relativna (postotna) promjena izlazne snage, specifične potrošnje goriva, potrošnje goriva i količine dimnih plinova ovisno o temperaturi zraka na usisu kompresora. Rast temperature zraka iznad ISO uvjeta degradira performanse turbine, smanjenjem izlazne snage i povećanjem specifične potrošnje goriva.

All gas turbine characteristics significantly change under various atmospheric conditions for incoming air. Such variations occurring on a daily basis may be great, although these variations are most evident when comparing winter and summer operation. Figure 2 shows the relative (percentile) variation in output power, specific fuel consumption, fuel consumption and the amount of flue gases dependent on air temperature at the compressor inlet. An increase in air temperature above the ISO norms degrades the performance of the turbine, reducing its output power and increasing the specific fuel consumption.



Slika 2 — Ovisnost karakteristika plinske turbine GE - PG 6101 FA o temperaturi zraka na usisu kompresora [2]
Figure 2 — Correlation between the GE - PG 6101 FA gas turbine characteristics and the air temperature at the compressor inlet [2].

Do degradacije performansi dolazi zbog toga što je gustoća zraka obrnuto proporcionalna temperaturi izmjerenoj mokrim termometrom, što znači da porastom temperature okolišnog zraka opada maseni protok zraka na usisu kompresora plinske turbine. Izlazna snaga plinske turbine direktno ovisi o masenom, a ne o volumnom

Degradation in performance occurs because the air density is inversely proportional to the temperature measured by a wet-bulb thermometer, meaning that with an increase in the ambient air temperature the airflow mass falls at the compressor inlet on the gas turbine. The output power of the gas turbine directly depends on the mass and not the airflow protoku zraka (volumni protok je konstantan, određen konstrukcijom plinske turbine). Na slici 2 prikazano je kako se promjena gustoće zraka ovisno o temperaturi očituje na performanse plinske turbine, pri čemu je vidljiv značajan utjecaj na:

— specifičnu potrošnju goriva,
— izlaznu snagu,
— protok dimnih plinova,
— potrošnju goriva.

Iz slike 2 je vidljivo da kao što povećanje temperature zraka degradira performanse, smanjenje temperature poboljšava performanse.

U praksi je uobičajena korekcija izlazne snage dijeljenjem nominalne snage pri ISO uvjetima s korekcijskim faktorom α koji uključuje ovisnost snage o vanjskoj temperaturi i relativnoj vlažnosti (formula 4) [2]. Korekcijski faktor α za turbinu GE - PG 6101 FA, kojeg je odredio proizvođač, prikazan je dijagramom na slici 3. Ovisnost izlazne snage o relativnoj vlažnosti je zanemariva, što je vidljivo iz dijagrama na slici 3. Pri temperaturama okoliša manjim od 10 °C relativna vlažnost nema utjecaja na izlaznu snagu plinske turbine, dok je pri temperaturama višim od 10 °C taj utjecaj zanemarivo malen (poklapanje vrijednosti faktora α pri različitoj relativnoj vlažnosti je u granici ± 1%). Jednako je zanemariv utjecaj relativne vlažnosti na ostale performanse plinske turbine te se u ovom radu ne promatra.

Korigirana izlazna snaga:

volume (volume flow is constant, and determined by the gas turbine construction). Figure 2 shows that a variation in air density dependant on temperature is evident in the performance of the gas turbine, with a clearly visible affect on:

— specific fuel consumption,
— output power,
— flue gas flow,
— fuel consumption.

Figure 2 clearly shows that as the increase in air temperature degrades performance, a reduction in temperature improves performance.

A correction of the output power by dividing the nominal power during ISO conditions with a corrective factor α that includes power dependent on the external temperature and relative humidity (formula 4) is standard procedure [2]. The correction factor α for the GE - PG 6101 FA turbine, defined by the manufacturer, is shown in the diagram in Figure 3. Dependency of the output temperature on relative humidity is negligible, as is evident from the diagram in Figure 3. At ambient temperatures less than 10 °C, relative humidity has no influence on the output power of the gas turbine, while at temperatures exceeding 10 °C this effect is negligibly small (correlation of the α factor value at different values for relative humidity is within the limits ± 1%). What is also negligible is the impact of relative humidity on the other performances of the gas turbine and therefore it is not taken into account in this work.

Corrected output power:

$$P_N^{kor} = \frac{P_N(15\ ^oC)}{\alpha}\ , \qquad (4)$$

gdje je:

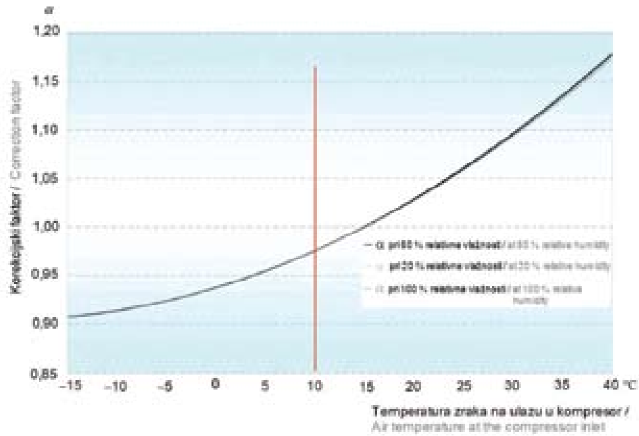
P_N^{kor} – korigirana nominalna snaga,
P_N – nominalna snaga pri ISO uvjetima,
α – korekcijski faktor.

Utjecaj atmosferskog tlaka na performanse plinske turbine također se ne razmatra, jer je atmosfersko obilježje lokacije na kojoj je turbina instalirana.

where:

P_N^{kor} – corrected nominal power,
P_N – nominal power,
α – corrective factor.

Impact of atmospheric pressure on the gas turbine performance is also not taken into account, since it is the atmospheric property of the location where the turbine is installed.



Slika 3 — Korekcijski faktor α koji ovisi o relativnoj vlazi i vanjskoj temperaturi zraka [2]

Figure 3 — Correction factor α which depends on relative humidity and external air temperature [2]

3 VRSTE I PRINCIP RADA SUSTAVA ZA HLAĐENJE ZRAKA NA USISU KOMPRESORA PLINSKE TURBINE

Mogućnost održavanja i poboljšanja nazivnih performansi smanjenjem temperature zraka na ulazu kompresora pokrenula je istraživanja i praktična ispitivanja tog područja. Do danas je razvijen veliki broj tehnika za hlađenje zraka na ulazu kompresora plinske turbine, a većina njih je primijenjena i u komercijalnoj uporabi. Te tehnike se prema funkciji i načinu rada dijele u sljedeće osnovne grupe [3] i [4] :

- evaporativno hlađenje:
  - strujanjem zraka kroz vlažni medij,
  - ušpricavanjem vode u obliku maglice,
  - ušpricavanjem vode u obliku maglice iznad zasićenja,
- klasični rashladni sustavi:
  - klasični rashladni sustav – direktni,
  - klasični rashladni sustav – indirektni,
  - klasični rashladni sustav sa spremnikom leda,
  - klasični rashladni sustav sa spremnikom smjese vode i leda,
- apsorpcijski rashladni sustavi:
  - apsorpcijski jednostupanjski rashladni sustav,
  - apsorpcijski dvostupanjski rashladni sustav,
- hlađenje uplinjavanjem LNG-a,
- hibridni rashladni sustavi.

Svaka od tih tehnika ima svoje dobre i loše osobine, koje se očituju kroz troškove investicije, troškove rada i održavanja, efikasnost, ali i kroz mogućnost primjene u ovisnosti o klimatskim uvjetima lokacije na kojoj je postrojenje izgrađeno.

3 TYPES AND PRINCIPLES OF OPERATION OF THE AIR COOLING SYSTEM AT THE GAS TURBINE COMPRESSOR INLET

The possibility of maintaining and improving declared performance by reduction in air temperature at the compressor inlet has initiated research and practical testing in this area. Up until today, a large number of techniques have been developed for cooling air at the compressor inlet in gas turbines, with most of them applied in commercial use. Such techniques are divided according to the function and manner of operation into the following basic groups [3] and [4]:

- evaporative cooling using:
  - air flow through a humid medium,
  - spraying water in the form of drops,
  - spraying water in the form of drops above saturation levels,
- classical cooling systems:
  - classical cooling system – direct,
  - classical cooling system – indirect,
  - classical cooling system with ice storage,
  - classical cooling system with a reservoir for water and ice mixture,
- absorption cooling system:
  - single-stage absorption cooling system,
  - two-stage absorption cooling system,
- cooling by gasification of LNG,
- hybrid cooling systems.

Each of these techniques has its positive and negative qualities, revealed thorough investment, operational and maintenance costs, efficiency, and through the possibilities of application depending on the climatic condition of the location where the plant has been assembled.

3.1 Evaporativno (tzv. mokro) hlađenje zraka

3.1.1 Strujanje zraka kroz vlažni medij

Strujanje zraka kroz vlažni medij je jedna od mokrih tehnika kojima se hlađenje postiže evaporacijom (hlapljenjem) vode koja se dodaje struji zraka na usisu kompresora. Povijesno gledano, to je prva komercijalno korištena tehnika hlađenja zraka na usisu kompresora. Tom tehnikom struja zraka se izlaže vodenom filmu koji prolazi nekom od mnogih primijenjenih vrsta vlažnih medija. U nekim slučajevima voda koja se koristi da ovlaži medij mora biti kemijski tretirana (pripremljena), ovisno o kemijskom sastavu sirove vode te o zahtjevima i specifikacijama proizvođača medija. Strujanjem kroz vlažni medij zrak se može ohladiti za oko 85 % do 95 % razlike između temperature mokrog i temperature suhog termometra okolišnog zraka.

Kod ovog načina hlađenja investicijski trošak, te troškovi rada i održavanja najniži su, ali njegov osnovni nedostatak je to što je dubina hlađenja ograničena temperaturom mokrog termometra, tj. učin je ovisan o atmosferskim uvjetima. Pored toga, u radu je potrebno stalno praćenje kemijskih karakteristika recirkulirajuće vode koja prolaskom kroz vlažni medij apsorbira nečistoće, te praćenje degradacije materijala ispune vlažnog medija.

Hlađenje zraka strujanjem kroz vlažni medij najefikasnije je u toplim i suhim klimatskim uvjetima, a efikasnost mu izrazito opada pri visokoj vlazi u zraku. Također, ovaj način u radu troši velike količine vode. Pored svih nedostataka, hlađenje strujanjem kroz vlažni medij je najrasprostranjenija i najviše korištena tehnika hlađenja zraka na usisu kompresora plinske turbine.

3.1.2 Ušpricavanje vode u obliku maglice

Ušpricavanje vode u obliku maglice sljedeća je mokra tehnika hlađenja koja se bazira na dodavanju sapnicama fino raspršene vode u struju zraka. Ušpricavanjem vode u obliku maglice zrak je moguće ohladiti za 95 % do 98 % razlike između temperature mokrog i temperature suhog termometra okolišnog zraka, pa je taj način samo malo efikasniji od strujanja vlažnim medijem. Sustavi za ušpricavanje uglavnom koriste kemijski pripremljenu (demineraliziranu) vodu, a mogu biti projektirani za različite veličine kapljica ovisno o željenom vremenu evaporacije (hlapljenja) te klimatskim uvjetima lokacije. Veličina kapljica je uglavnom manja od 40 μm, dok je u većini slučajeva približno 20 μm.

Troškovi ovog načina hlađenja vrlo su slični troškovima pri hlađenju strujanjem zraka kroz vlažni medij, a također su slična i ograničenja i nedostaci. Ušpricavanje vodene maglice u struju zraka na drugom je mjestu po zastupljenosti u instali-

3.1 Evaporative (Wet) Air Cooling

3.1.1 Air Circulation Through a Moist Medium

Circulation of air through a moist medium is one of the wet techniques whereby cooling is achieved by evaporation of water which is added to the circulating air at the compressor inlet. Viewed historically, this was the first commercially used technique for cooling air at the compressor inlet. This air circulation technique is exposed to film of water passing through some of the many applicable types of moist mediums. In some cases, water used in order to moisten the medium must be chemically treated (prepared), depending on the chemical composition of the raw water and the requirements and specifications by the medium manufacturer. Circulation through the moist medium allows air to be cooled by around 85 % to 95 % of the difference between the moist and dry ambient air temperature.

For this type of cooling, the investment, operational and maintenance costs are lower, but its main deficiency is that the depth of cooling is limited by the temperature of the wet-bulb thermometer, i.e. the result depends on the atmospheric conditions. Furthermore, during operation, continual monitoring is necessary of the chemical characteristics of the re-circulated water which, passing through the moist medium, absorbs impurities, and the monitoring of the degradation of materials filling the moist medium.

Cooling air by circulating it through a moist medium is optimally effective in hot and dry climatic conditions, whereas its efficiency deteriorates exceptionally at very high air humidity. Moreover, this manner of operation uses large quantities of water. Besides these inadequacies, cooling by circulation in a moist medium is the most common and widely used technique for cooling air at the compressor inlet on gas turbines.

3.1.2 Spraying Water in Drop Forms

Spraying water in drop forms is the next wet cooling technique, which is based on adding finely dispersed water in the circulating air by nozzles. By spraying water in drop forms, air is cooled by 95 % to 98 % of the difference between the dry and wet temperature of an ambient air thermometer, hence this method is only somewhat more efficient than circulating air in a moist medium. Spraying systems mainly use chemically prepared (demineralised) water, and can be designed for various drops sizes depending on the desired evaporation time and climatic conditions at the location. The size of the drops is mainly less than 40 μm while in the majority of cases they are approximately 20 μm.

The costs of this type of cooling are very similar to the costs associated with cooling by circulating air ranim sustavima hlađenja, iako pojedini proizvođači i korisnici plinskih turbina ne dozvoljavaju njegovu primjenu zbog moguće degradacije karakteristika i mogućih kvarova kompresora, koji se pripisuju ušpricavanju.

3.1.3 Ušpricavanje vode u obliku maglice iznad zasićenja

Ušpricavanje vode u obliku maglice iznad zasićenja treća je mokra tehnika hlađenja u kojoj se ušpricava više vodene maglice u struju zraka nego što je moguće da ishlapi pri okolišnim uvjetima. Struja zraka, u tom slučaju zasićena do 100 % relativne vlage, višak ušpricane vode u obliku maglice unosi u kompresor, gdje ona pri promjeni tlaka i temperature zraka dodatno hlapi i hladi komprimirani zrak, stvarajući tako dodatni maseni protok koji povećava izlaznu snagu plinske turbine u većoj mjeri nego je to moguće klasičnim evaporativnim sustavima hlađenja. Ova tehnika zahtijeva vodu visoke kvalitete, jer bi u protivnom troškovi održavanja nastali zbog vode loše kvalitete mogli biti veći nego ekonomski efekt poboljšanja karakteristika hlađenjem zraka.

3.2 Klasični rashladni sustavi

Klasičnim rashladnim sustavima moguće je rashladiti ulaznu struju zraka do temperatura mnogo nižih nego su to u stanju evaporativni sustavi hlađenja, te je bez obzira na vlagu u zraku i temperaturu mokrog termometra moguće postići i održavati temperaturu zraka na bilo kojoj vrijednosti do minimalnih 5 °C. Rashladni sustavi mogu biti pogonjeni električnim motorima, ili parnim turbinama. Hlađenje se u tom slučaju odvija strujanjem zraka preko cijevnog snopa izmjenjivača topline postavljenog iza usisnih filtara zraka, kroz koji struji rashladni medij ili ohlađena voda i hladi zrak na željenu temperaturu.

Opće prednosti klasičnog rashladnog sustava su da se njime može postići i održati željena temperatura zraka neovisno o atmosferskim i klimatskim uvjetima. Nedostaci ovog načina hlađenja su veći troškovi investicije, rada i održavanja. Klasični rashladni sustavi pogonjeni elektromotorima povećavaju vlastitu potrošnju proizvodne jedinice, jer za svoj pogon troše dio proizvedene električne energije. Za razliku od evaporativnih sustava, da bi proizveli rashladni učin malim dijelom smanjuju predanu snagu proizvodne jedinice, ali takva usporedba s mokrim sustavima nije vjerodostojna, jer je njihova primjena uglavnom na lokacijama na kojima zbog atmosferskih i klimatskih uvjeta evaporativni sustavi nemaju značajnog efekta, tj. na lokacijama gdje je relativna vlaga u zraku visoka.

through a moist medium, and the limitations and inadequacies are also similar. Spraying water drops into the circulating air is the second most common method in installed cooling systems, although certain gas turbine manufacturers and users do not allow such use due to possible degradation of characteristics and compressor breakdowns associated with spraying.

3.1.3 Spraying Water into Drop Forms Above Saturation Levels

Spraying water in the drop forms above the saturation level is the third most popular cooling technique whereby more water drops are sprayed into the circulating air than can evaporate at ambient conditions. The circulating air, in this case saturated at 100 % relative air humidity, excess sprayed water in the form of drops enters the compressor, creating therefore additional mass flow which increases the output power of the gas turbine to a greater extent than possible when using classical evaporative cooling systems. This technique requires high-quality water, since, in the opposite case, maintenance costs occurring due to poor water quality might be greater than the economic effect of improving air-cooling characteristics.

3.2 Classical Cooling Systems

Classical cooling systems can cool incoming circulating air up to a temperature much lower than is possible by evaporative cooling systems, and regardless of the air humidity and temperature of the wet thermometer, these can achieve and maintain air temperatures at any value up to a minimum of 5 °C. Electrical motors or steam turbines can drive cooling systems. Cooling in this case is conducted by circulating air through a series of tubes in a heat exchanger placed behind the inlet air filters, through which the cooling medium or cooled water and cooled air circulate at the desired temperature.

The general advantages of the classical cooling system are that it can achieve and maintain desired air temperatures regardless of the atmospheric and climatic conditions. The disadvantages of this manner of cooling are higher investment, operational and maintenance costs. Classical cooling systems driven by electrical motors increase consumption at the production unit since part of the produced electrical power is used for operation.

In order to produce a cooling effect, compared to evaporative systems, classical cooling systems reduce power supplied from the production unit to a lesser extent. But such comparisons with wet systems are not reliable, because their use occurs mainly at locations where, due to atmospheric and climatic conditions, evaporative systems do not have a significant effect, i.e. at locations with relatively high air humidity.

Razlikuju se:

- direktni klasični rashladni sustav – sustav kod kojeg rashladni medij (uglavnom amonijak) neposredno iz rashladnog uređaja prolazi kroz cijevi hladnjaka zraka na ulazu kompresora,
- indirektni klasični rashladni sustav – za razliku od direktnog uvodi još jedan cirkulacijski krug vode, koja se hladi rashladnim medijem (uglavnom amonijak) iz rashladnog uređaja, te tako ohlađena prolazi kroz cijevi hladnjaka zraka na ulazu kompresora,
- klasični rashladni sustav sa spremnikom leda – kao i klasični rashladni sustav sa spremnikom smjese vode i leda koristi akumulaciju leda ili hladne smjese vode i leda. Ovakav način se koristi kod postrojenja kojima u tarifnim sustavima cijene isporučene energije bitno odstupaju između vršnih i normalnih sati. Akumulacijom je omogućen kontinuirani rad rashladnog uređaja s manjim opterećenjem, jer se izvan vršnih sati hladi spremnik, iz kojeg se u vršnim satima tarifnog sustava povlači rashladna tekućina te se dobiva mnogo veći rashladni kapacitet nego je kapacitet rashladnog sustava. Parazitska potrošnja električne energije rashladnog sustava i time nastalo povećanje vlastite potrošnje proizvodne jedinice na taj način se pomiče u vrijeme izvan vršnih sati.

3.3 Apsorpcijski rashladni uređaji

Apsorpcijski rashladni uređaji funkcionalno su slični klasičnim rashladnim uređajima, s bitnom razlikom da umjesto mehaničkog rada elektromotora ili parne turbine za proizvodnju rashladnog učina koriste vanjski izvor toplinske energije, koja im se dovodi vrućom vodom ili vodenom parom. Njihov konzum električne energije daleko je manji, jer je potreban samo za pumpe cirkulacije rashladne vode. Apsorpcijski rashladni uređaji mogu ohladiti zrak do temperature od oko 10 °C, a mogu se poput klasičnih rashladnih sustava koncipirati sa ili bez akumulacijskih spremnika leda ili smjese leda i vode. Razlikuje se:

- jednostupanjski apsorpcijski rashladni uređaji kao vanjski izvor toplinske energije koriste vruću vodu ili pregrijanu paru tlaka približno 2 bar,
- dvostupanjski apsorpcijski rashladni uređaji koji za isti učin troše osjetno manje količine pare, ali je potrebna para viših parametara, oko 9 bar.

Prednost ovih sustava je da ne opterećuju vlastitu potrošnju proizvodne jedinice, tj. opterećuju je vrlo malo u odnosu na klasične rashladne

The following are distingushed:

- direct classical cooling systems – a system whereby the cooling medium (most often ammonia) passes directly from the cooling system through the piping of the air cooler at the compressor inlet,
- indirect classical cooling system – introduces, in comparison to the direct system, still another water circulation cycle, cooled using a cooling medium (most often ammonia) from the cooling device, and therefore once cooled passes through the piping of the air cooler at the compressor inlet,
- the classical cooling system with an ice reservoir – as in the classic cooling systems with a reservoir containing a mixture of water and ice, this system uses an accumulation of ice or a cold mixture of water and ice. This technique is used for plants where the tariff price system for delivered power deviates greatly from the peak or normal hours. Accumulation allows continual operation of the cooling device and less loading, since, outside of the peak hours, the reservoir is cooled, and during the tariff system peak hours, from the reservoir the cooling liquid is used and a much larger cooling capacity is gained than is the capacity in a cooling system. Parasitic consumption of electrical power in the cooling system and therefore the increase in proprietary consumption by the production unit is transferred to the time periods outside of the peak hours.

3.3 Absorption Cooling Devices

Absorption cooling devices are functionally similar to classical cooling devices, with the main difference being that instead of mechanical operation of the electrical motor or steam turbine for the production of the cooling effect, an external source of thermal energy is used sourced from hot water or water steam. Their consumption of electrical power is far less, since such power is necessary only for the cooling water circulation pumps. The absorption cooling devices can cool air up to a temperature of around 10 °C, and just like the classical cooling systems, these can be designed with or without accumulation reservoirs for ice or ice-water mixtures. The following differences exist:

- single-stage absorption cooling devices as the external source of thermal energy use hot water or heated steam at a pressure of approximately 2 bar,
- two-stage absorption cooling devices for the same effect use considerably lesser amounts of steam, but steam at higher parameters of around 9 bar is necessary.

The advantages of these systems is that they do not exert proprietary consumption from the production sustave pogonjene elektromotorom, no investicijski troškovi su značajno veći nego kod klasičnih rashladnih sustava. Apsorpcijski sustavi se prvenstveno primjenjuju u termoenergetskim objektima gdje postoji jeftina toplinska energija čijom je pretvorbom u rashladni učin moguće proizvesti dodatnu skupu električnu energiju.

3.4 Hlađenje zraka uplinjavanjem LNG-a

Hlađenje uplinjavanjem tekućeg prirodnog plina (LNG) primjenjuje se kod postrojenja smještenih u blizini terminala za uplinjavanje tekućeg prirodnog plina. Proces uplinjavanja LNG-a zahtjeva izvor topline, te se primjenom cirkulacijskog kruga vode između hladnjaka zraka na usisu kompresora i isparivača tekućeg plina ta toplina dovodi iz struje zraka koja ulazi u kompresor plinske turbine. Kod ovakvog načina hlađenja zraka investicijski troškovi i troškovi održavanja sustava su jedini, jer se njegovim radom supstituira jedan dio ionako potrebnog izvora toplinske energije za isparivač tekućeg plina.

3.5 Hibridni rashladni sustavi

Hibridni rashladni sustavi kombiniraju pojedine od spomenutih tehnika, npr. klasični i apsorpcijski rashladni sustav. Takvi sustavi se projektiraju i optimiraju prema posebnim zahtjevima na pojedine elektrane ovisno o traženim količinama isporučene električne energije i njenim cijenama, te raspoloživosti toplinske energije.

Na slici 4 prikazan je hladnjak zraka ugrađen u filtarsku jedinicu usisnog kanala kroz koji kompresor usisava zrak iz okoline. Hladnjak se ugrađuje iza filtra zraka, a njegovim smještajem u struji zraka omogućeno je njeno hlađenje, tj. odvođenje topline rashladnim medjem. Hladnjaci se ugrađuju kod klasičnih, apsorpcijskih ili hibridnih rashladnih sustava. Kod evaporativnih sustava na istom mjestu potrebno je ugraditi postolja sa sapnicama za ubrizgavanje vode, ili nosače važnog medija, ovisno o vrsti mokrog sustava hlađenja. Rekonstrukcija i proširenje filtarske jedinice hladnjakom ujedno je i jedini zahvat na plinskoturbinskom agregatu. Ostali dijelovi sustava hlađenja su periferni, pomoćni sustav koji ne mijenja i ne zadire u konstrukciju plinske turbine.

4 ODRŽAVANJE PERFORMANSI PLINSKE TURBINE HLAĐENJEM ZRAKA NA ULAZU U KOMPRESOR

Ovisnost osnovnih performansi plinske turbine (specifične potrošnje goriva, izlazne snage, pro-

units, i.e. such loading is very small with respect to classical cooling systems driven by electrical motors, but the investment costs are considerably greater than with classical cooling systems. The absorption systems are primarily used in thermal power plants where there exists cheap thermal energy whose transformation into a cooling effect produces additionally expensive electrical power.

3.4 Air-Cooling By Gasification of LNG

Cooling using gasification of liquefied natural gas (LNG) is used in plants located close to terminals for gasification of liquefied natural gas. The process of gasification of LNG requires a thermal source, and in using the water circulation cycle between the air coolers at the compressor inlet and the liquefied gas evaporator, this heat is brought from the airflow entering the gas turbine compressor. This manner of cooling air exerts only investment and maintenance costs for the system, since its operation replaces part of the already necessary source of thermal energy for the liquefied gas evaporator.

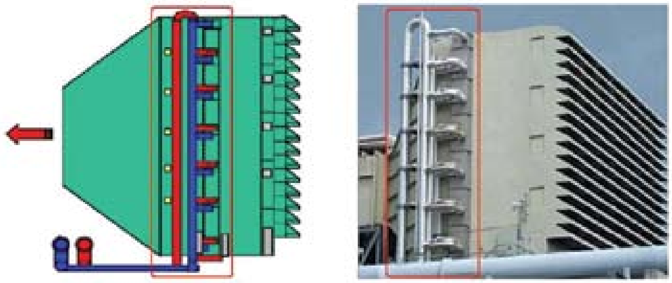
3.5 Hybrid Cooling System

Hybrid cooling systems combine various parts of the stated techniques, for instance, the classical and absorption cooling system. Such systems are designed and optimised according to particular requirements for certain power stations and depending on the required amounts of delivered electrical power and prices, as well as the availability of thermal energy.

Figure 4 shows the air cooler installed into the filter unit of the inlet canal through which the compressor sucks air from the surroundings. The cooler is fitted behind the air filter, while its position in the airflow allows it to be cooled, i.e. removal of the heat from the cooling medium. The coolers are installed in classical, absorption or hybrid cooling systems. For evaporative systems located at the same position, it is necessary to install a base with nozzles for accelerating water, or carriers for the moist medium, depending on the type of wet cooling system. Reconstruction and expansion of the filter units using the cooler is actually the only intervention on the gas turbine generator. The other parts of the cooling system are peripheral, auxiliary systems that do not alter or affect the gas turbine construction.

4 MAINTAINING PERFORMANCE OF THE GAS TURBINE BY COOLING AIR AT THE COMPRESSOR INLET

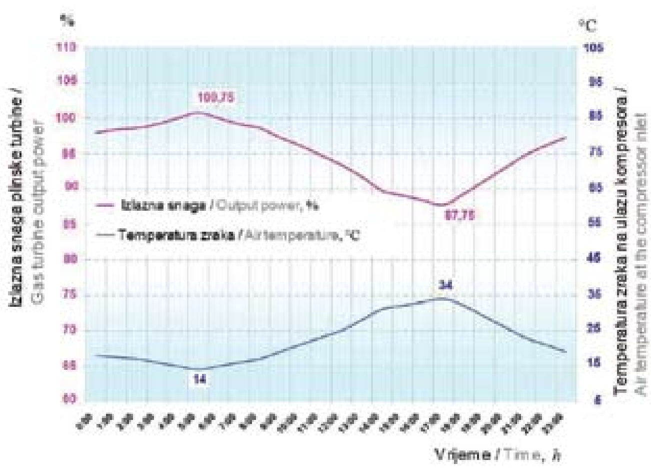
Dependency of the gas turbine's fundamental performance (specific fuel consumption, output power,



Slika 4 — Hladnjak zraka smješten u filtarskoj jedinici usisnog kanala zraka
Figure 4 — Air cooler located in the filter unit of the air inlet canal

toka dimnih plinova i potrošnje goriva) o temperaturi na ulazu u kompresor prikazana je na slici 2. Na slici 5 prikazan je dijagram promjene izlazne snage plinske turbine u tipičnom ljetnom danu, u odnosu na doba dana i temperaturu okoliša.

flue gas flow and fuel consumption) on the temperature at the compressor inlet is shown in Figure 2. Figure 5 shows the diagram for gas turbine output power variation in a typical summer day with respect to the time of day and ambient temperature.



Slika 5 — Ovisnost izlazne snage plinske turbine o temperaturi zraka na usisu kompresora u tipičnom ljetnom danu
Figure 5 — Dependency of gas turbine output power on the air temperature at the compressor inlet during a typical summer day

Apscisa dijagrama na slici 5 je vrijeme, te je kao vremenski okvir odabrano 00:00 do 24:00 sata. Skala na lijevoj ordinati prikazuje postotni iznos nominalne snage plinske turbine pri ISO uvjetima, gdje je 100 % nazivne snage vezano uz temperaturu od 15 °C. Desna ordinata prikazuje temperaturu okoliša, koja je ujedno i temperatura zraka na ulazu kompresora.

Donja krivulja pokazuje promjenu temperature zraka kroz dan, a gornja krivulja promjenu izlazne snage ovisno o temperaturi okoliša prema dijagramu na slici 2. Indikativan je značajni pad izlazne snage plinske turbine od 12,25 % pri temperaturi od 34 °C, koja se na dijagramu pojavljuje između 17:00 i 18:00 sati, što je kod turbine GE - PG 6101 FA gotovo 8,5 MW.

The x-axis on the diagram in Figure 5 is time, and the time period chosen covers 00:00 to 24:00 hours. The scale on the left ordinates shows the percentage value of the gas turbine's nominal power at ISO conditions, where 100 % of the nominal power relates to a temperature of 15 °C. The right ordinate shows the ambient temperature, which is also the air temperature at the compressor inlet.

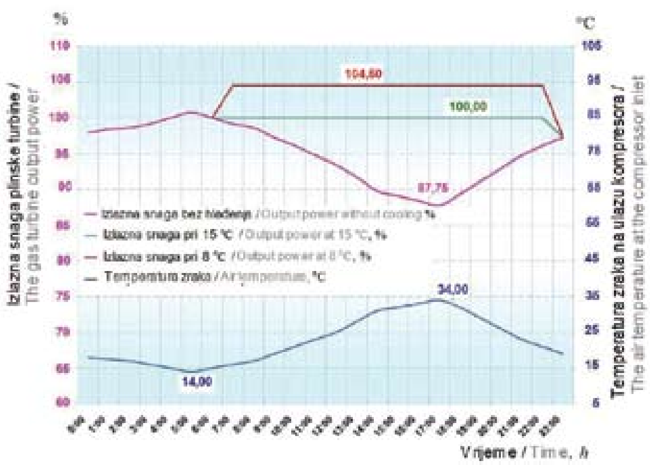
The lower curve shows the air temperature variation during the day, while the upper curve shows the variation in output power with respect to the ambient temperature as shown in the diagram in Figure 2. What is indicative is the significant reduction of 12,25 % in output power of the gas turbine at temperatures of 34 °C occurring on the diagram between 17:00 and 18:00 hours, which for the GE – PG 6101 FA turbine is almost 8,5 MW.

Ovdje je istaknuta maksimalna degradacija snage, ali je iz dijagrama uočljivo da je degradacija snage prisutna cijelo vrijeme u kojem je temperatura viša od 15 °C. Da bi se ta degradacija spriječila, okolišni zrak se na ulazu u kompresor hladi. Efekt hlađenja zraka, tj. utjecaj na izlaznu snagu prikazan je dijagramom na slici 6, u istom vremenskom okviru i istim ordinatama.

Ključni trenuci prikazani dijagramom na slici 6 su start rashladnog sustava hlađenja zraka, koji se po dijagramu potrošnje električne energije događa između 06:00 i 07:00 sati ujutro. Zelena i crvena krivulja predstavljaju izlaznu snagu plinske turbine u periodu rada rashladnog sustava. Mogući načini rada su održavanje ulazne temperature zraka na 15 °C, što je prikazano zelenom krivuljom, te eliminiranje degradacije izlazne snage plinske turbine s porastom temperature. Na taj način turbinu održavamo na njenim nominalnim parametrima pri ISO uvjetima.

Here the maximum degradation in power is emphasised, but is can be concluded from the diagram that the degradation in power is present during the whole time in which the temperature is greater than 15 °C. In order to prevent this degradation, the surrounding air at the compressor inlet is cooled. The effect of cooling the air, i.e. the effect on the output power is shown by the diagram in Figure 5, in the same time period and same axis.

The key moments shown in the diagram in Figure 6 are the starting of the cooling system for cooling the air, which according to the diagram for electrical power consumption occurs between 06:00 and 07:00 hours in the morning. The green and red curves represent the gas turbine's output power in the period of operation of the cooling system. The possible modes of operation are maintaining the output air temperature at 15 °C, shown by the green curve, and an elimination of the degradation of the gas turbine's output power at temperature increases. In this way, the turbine is maintained at its nominal parameters at ISO conditions.



Slika 6 — Utjecaj hlađenja zraka na izlaznu snagu plinske turbine tijekom tipičnog ljetnog dana

Figure 6 — The impact of cooled air on the gas turbine's output power during a typical summer day

Dodatna pogodnost dobro kapacitiranog rashladnog sustava je hlađenje zraka na temperaturu nižu od 15 °C prema kojoj je ISO uvjetima određena nominalna snaga, te porast izlazne snage zbog toga. Taj način rada prikazan je crvenom krivuljom, gdje je kao ciljana temperatura ohlađenog zraka odabrano 8 °C, a čime se dobiva porast izlazne snage plinske turbine od 4,5 % u odnosu na nominalnu. Usporedbom krivulja snage bez hlađenja zraka, te krivulje hlađenja na 8 °C pri okolišnoj temperaturi zraka od 34 °C, dobivena je razlika od 16,75 % nominalne snage, ili za turbinu GE - PG 6101 FA gotovo 11,5 MW.

Pored prikazanog utjecaja temperature zraka na izlaznu snagu, po istoj logici je napravljen dija-

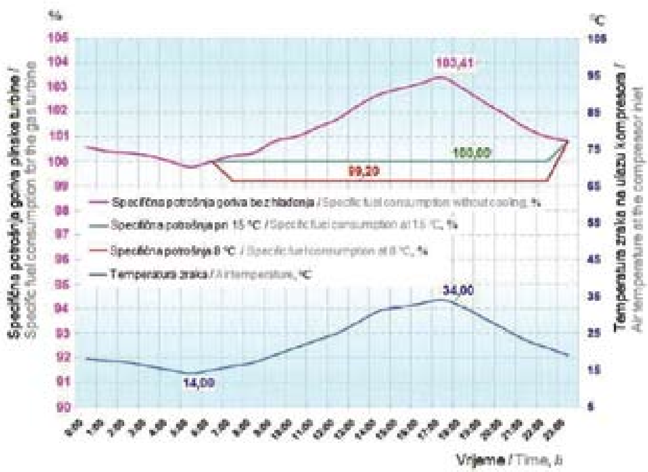
Additional benefits of a well-capacitated cooling system is cooling air at a temperature lower than 15 °C based upon which ISO conditions determine the nominal power, and the resulting increase in output power. This manner of operation is shown by the red curve, where the desired temperature of the cooled air is chosen as 8 °C, and where a 4,5 % increase in the gas turbine power output of 4,5 % is achieved compared to the nominal power output. A comparison of power curves without air cooled, and the cooling curve 8 °C at an ambient temperature of 34 °C, achieves a difference of 16,75 % in nominal power or almost 11,5 MW for the GE – PG 6101FA turbine.

Besides the shown impact of air temperature on output power, the same logic applies to the diagram utjecaja temperature okoliša na specifičnu potrošnju goriva, prikazan na slici 7.

Promatrajući iste uvjete kao i kod ovisnosti izlazne snage plinske turbine, iz dijagrama na slici 7 vidljivo je povećanje specifične potrošnje goriva pri povećanju temperature okoliša, tj. zraka koji ulazi u kompresor plinske turbine. Održanjem temperature na ISO uvjetima, specifična potrošnja goriva ostaje na svojoj nominalnoj vrijednosti, ili se hlađenjem zraka na 8 °C ona smanjuje. Pri tome se ne smanjuje apsolutna potrošnja goriva, koja je proporcionalna izlaznoj snazi, već se postiže ekonomičniji rad turbine, tj. potrebna količina goriva za proizvedenu električnu energiju je manja. Sukladno tome, i emisije dimnih plinova po proizvedenom kilovatsatu električne energije su manje.

gram showing the impact of the surrounding temperature on the specific fuel consumption, as shown in Figure 7.

Taking into consideration the same conditions as for output power dependency of the gas turbine, the diagram in Figure 7 clearly shows the increase in specific fuel consumption during increased ambient temperatures, i.e. air entering the gas turbine compressor. By maintaining the temperature at ISO conditions, the specific fuel consumption remains at its nominal value, or by cooling air to 8 °C, it falls. Consequently, the absolute fuel consumption which is proportional to the output power does not fall, but higher efficiency of turbine operation is achieved, i.e. the necessary amount of fuel for the produced electrical power is less. Therefore, the emission of flue gases for every produced kilowatt-hour of electrical power is lesser.



Slika 7 — Ovisnost specifične potrošnje goriva plinske turbine o temperaturi zraka na usisu kompresora u tipičnom ljetnom danu (s hlađenjem zraka, i bez hlađenja)

Figure 7 — Dependency of specific fuel consumption for gas turbines and the air temperature at the compressor inlet during a typical summer day (with and without air cooling)

5 ZAKLJUČAK

Hlađenje zraka na ulazu u kompresor plinske turbine danas je razvijena i poznata tehnika, višestruko potvrđena u eksploataciji. Osnovni razlog njene primjene je taj što pri povišenim temperaturama okolišnog zraka plinske turbine gube snagu zbog konstantnog volumnog, ali smanjenog masenog protoka zraka, koji je povećanjem temperature sve rjeđi i čiji se specifični volumen u tom slučaju povećava. Ovisno o klimatskim uvjetima lokacije na kojoj je postrojenje sagrađeno, taj efekt je više ili manje značajan, te je za svaku pojedinu lokaciju potrebno provjeriti ekonomičnost investicije u rashladni sustav. Ekonomičnost investicije ovisi prvenstveno o atmosferskim uvjetima, ali bitni parametri su i vrsta postrojenja, stanje elektroenergetskog su-

5 CONCLUSION

Today, cooling air at the compressor inlet of the gas turbine is a well-developed and common technique, confirmed many times through exploitation. The fundamental reason for its use is that during increased ambient air temperatures, gas turbines loose their power due to constant volume, but reduced air mass flow, which with increasing temperature is less dense and the specific volume of which increases in such cases. Depending on the climatic conditions of the location where the plant has been assembled, this effect is more or less important, and for each particular location, it is necessary to verify the economic viability of investing in a cooling system. Economic viability primarily depends on the atmospheric conditions, but also other important parameters include the type of plant, the state of stava na koji je vezan, te tarifni sustav naplate isporučene električne energije.

Na lokacijama na kojima se potvrdi opravdanost ugradnje rashladnog sustava, efekti ugradnje očituju se kroz eksploataciju maksimalnog učina postojećeg postrojenja, tj. eliminira se potreba izgradnje dodatnog vršnog izvora električne energije koji je elektroenergetskom sustavu potreban kada se superponira ljetna vršna potrošnja električne energije i efekt degradacije snage turbine pri visokim dnevnim temperaturama. U tom slučaju nema potrebe za ishođenjem dozvola i suglasnosti za izgradnju dodatnog izvora, oprema rashladnog sustava zauzima manje prostora nego novi izvor, a i troškovi pogona i održavanja rashladnog sustava su manji u odnosu na troškove pogona i održavanja dodatnog izvora.

Ekološki efekt se očituje kroz smanjenu specifičnu potrošnju goriva, tj. direktno smanjenje emisija u okoliš po proizvedenom kilovatsatu električne energije.

the electrical power system to which it is connected, and the tariff payment system for the supplied electrical power.

At locations where the constructing a cooling system is justified and confirmed, the effects of installing the system are evident in the exploitation of the maximum effect in the existing plant, i.e. elimination of the need to construct an additional peak source of electrical power necessary for the electrical power system when the summer peak consumption of electrical power and the effect of a degradation of the turbine's power is superimposed during high daily temperatures. In this instance, there is no need for obtaining a permit and consent for construction of an additional source; the cooling system equipment consumes less space than the new source, and the costs of the plant and maintenance of the cooling system are lesser compared to the costs associated with the plant and maintenance of the additional source.

The environmental effects are evident in reduced specific fuel consumption, i.e. a direct reduction in emissions into the environment for each produced kilowatt-hour of electrical power.

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   [4] J. W. ROZENBLIT A conceptual basis for model-based system design, PhD. Thesis, Wayne State University, Detroit, Michigan, 1985

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[1] FRAZIER, L., FODOR, J. D., The sausage machine: A new two-stage parsing model, Cognition, 6 (1978)
Book
[2] NAGAO, M., Knowledge and Inference, Academic Press, Boston, 1988 Conference
Paper
[3] R. L. WATROUS, L. SHASTRI Learning phonetic features using connectionist networks: An experiment in speech recognition. Presented at the Proceedings of the IEEE International Conference on Neural Networks, (1987) San Diego, CA
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