Univerza v Mariboru
Fakulteta za energetiko

Journal of ENERGY TECHNOLOGY

Volume 2 / Issue 4
NOVEMBER 2009
www.fe.uni-mb.si/si/e-jet/index.php

JOURNAL OF ENERGY TECHNOLOGY

VOLUME 2 / Issue 4

Revija Journal of Energy Technology (JET) je indeksirana v naslednjih bazah: INSPEC©, Cambridge Scientific Abstracts: Abstracts in New Technologies and Engineering (CSA ANTE), ProQuest's Technology Research Database.

The Journal of Energy Technology (JET) is indexed and abstracted in the following databases: INSPEC©, Cambridge Scientific Abstracts: Abstracts in New Technologies and Engineering (CSA ANTE), ProQuest's Technology Research Database.

JOURNAL OF ENERGY TECHNOLOGY

Ustanovitelji / FOUNDERS

Fakulteta za energetiko, UNIVERZA V MARIBORU /
FACULTY OF ENERGY TECHNOLOGY, UNIVERSITY OF MARIBOR

Izdajatelj / PUBLISHER

Fakulteta za energetiko, UNIVERZA V MARIBORU /
FACULTY OF ENERGY TECHNOLOGY, UNIVERSITY OF MARIBOR

Tehniška podpora / TECHNICAL SUPPORT

Janko OMERZU
Sonja NOVAK

Izhajanje revije / PUBLISHING

Revija izhaja štirikrat letno v nakladi 300 izvodov. Članki so dostopni na spletni strani revije - http://www.fe.uni-mb.si/si/e-jet/index.php .

The journal is published four times a year. Articles are available at the journal's home page - http://www.fe.uni-mb.si/si/e-jet/index.php .

Lektoriranje / Language Editing

Terry T. JACKSON

Produkcija / PRODUCTION

Vizualne komunikacije comTEC d.o.o.

Oblikovanje revije in znaka revije / JOURNAL AND LOGO DESIGN

Andrej PREDIN

V spomin Prof.dr. Matjažu Ravniku (1953-2009)

Matjaž Ravnik je bil široko mednarodno priznan strokovnjak na področju jedrskih reaktorjev. Vodil je Reaktorski infrastrukturni center IJS in tako skrbel za slovenski raziskovalni jedrski reaktor TRIGA. Nedavno je postal vodja programske skupine Reaktorska fizika. Tekom celotnega profesionalnega življenja je bil povezan z JE Krško, med drugim na področju računskih razvoja metod ali kot nadzornik. Zavzeto je poučeval mlade jedrske strokovnjake in predaval Fiziko ter Radiacijsko in reaktorsko fiziko za dodiplomske študente ter več predmetov za podiplomske študente. Pet disertacij in večje število magisterijev ter diplom je bilo narejenih pod mentorstvom prof. Ravnika.

S strani IAEA je bil poslan na večje število misij, med drugim v države kot so Peru, Tajska, Maroko. Matjaž Ravnik je bil je predsednik Strokovnega sveta za sevalno in jedrsko varnost, nacionalni koordinator za področje energetike pri MŠZŠ, član EU delovne skupine za načrtovanje prve fuzijske jedrske elektrarne DEMO, član varnostnega odbora JE Krško, član Znanstvenega sveta IJS, član Strokovne komisije za jedrsko varnost pri URSJV in podpredsednik državne komisije za preverjanje znanja operaterjev. Imel je še vrsto drugih funkcij in bil viden član Mednarodne skupine za evaluacijo testnih eksperimentov, Društva jedrskih strokovnjakov in Znanstvenega sveta revije *Journal of Energy technology*.

V primeru, da bi bilo potrebno osebo Matjaževa Ravnika opisati zgolj z eno besedo bi ga najbolje opisali s pojmom moder. S svojim znanjem ni izstopal zgolj na področju reaktorske znanosti ampak na vseh področjih, ki se jih je lotil. Pred dvema desetletjema je kot eden izmed prvih začel opozarjati na danes zelo aktualno problematiko podnebnih sprememb. Tako je že leta 1997 napisal vodilno slovensko knjigo na to temo – Topla greda: podnebne spremembe, ki jih povzroča človek. V zelo dobro napisani knjigi je že takrat prav vizionarsko predvidel veliko stvari, ki se desetletje kasneje v resnici udejanjajo. Tako je možno sklepati, da se bodo uresničile tudi stvari, ki jih knjiga v zvezi s klimatskimi spremembami napoveduje za naslednja desetletja. Matjaž se je, zaradi prevelike spolitiziranosti vprašanja podnebnih sprememb, v zadnjem času v javnosti prenehal ukvarjati s to temo, kljub temu, da ga zanimanje zanjo ni minilo. To opisuje tudi eno izmed njegovih značilnih lastnosti, namreč nekonfliktnost.

Vsake stvari, ki se je lotil, je namenil veliko pozornosti. Tako mu je bilo pravi užitek prisluhniti, ko je začel razglabljati o katerikoli tem, ki ga je zanimala, pa naj so bili to politični problemi, religija ali o gozdarstvo v Kočevskih gozdovih. Z izjemno vnemo se je posvečal tudi svojim študentom. V primeru, da je študent ali sodelavec prišel k njemu s problemom je po navadi postavil na stran vse drugo delo in se mu posvetil. Tako se je dogajalo, da se je pred fakulteto s študenti pogovarjal še uro ali dve po zaključku svojih predavanj. Matjaž je za sabo pustil veliko vrzel na področju reaktorske fizike v Sloveniji, a je veliko svojega znanja prelil na več sodelavcev, ki bodo lahko tudi na tej podlagi črpali za prihodnost. Še večja pa je vrzel, ki je ostala za Matjažem kot človekom.

In memoriam to Prof. dr. MATJAŽ RAVNIK (1953-2009)

Matjaž Ravnik was an internationally widely recognized expert for the field of nuclear reactors. He was the head of the Reactor Infrastructure Center of the JSI, taking care of Slovenia research nuclear reactor TRIGA and recently became the head of the Reactor Physics research group. During all of his professional life he was connected to the Krško NPP, either by developing calculational techniques or as a supervisor. He was very devoted to raising young nuclear scientists and was teaching the courses on Physics and on Reactor and Radiation Physics for undergraduate students and several graduate courses. Five dissertations and numerous M.Sc. and B.Sc. theses were prepared under prof. Ravnik's tutorship.

He was send to several missions by the IAEA, among others to the countries like Peru, Thailand, and Morocco. He also held the positions of the president of the National Nuclear and Radiation Safety Council, was the national research coordinator for the research field energy at MHEST and was member of the EU fusion power plant project DEMO, Krško NPP Safety Commission, Nuclear Safety Commission of the SNSA, J. Stefan Institute Scientific Council and national reactor operator examination commission. He held numerous other positions and was a notable member of the International Criticality Safety Benchmark Evaluation Working Group the Nuclear Society of Slovenia and the Scientific Council of the Journal of Energy Technology.

If one was given the task to describe the personality of Matjaž Ravnik with a single word, the word of choice would be "wise". His knowledge was outstanding not only in his professional filed of reactor physics but in all fields he came in contact with. Two decades ago he was among the first to call for attention about the consequences of global warming, a topic widely discussed nowadays. In 1997 he wrote the main Slovenian book on this topic – Greenhouse effect: climate changes caused by mankind. In this excellent book he has already at that time visionary foreseen many thing, that are happening a decade latter. It could be judged that many things, described in the book, may come true in the decades to come. Matjaž stopped attending meetings on climate change due to the political abuse of the topic, although he was still interested in it. This pictures another side of his personality, namely his wish to avoid conflicts.

He devoted a lot of care to everything he was dealing with. It was a pleasure to listen to him when he was talking about anything in his interest, either was this politics, religion or the management of the forests around Kočevje. He was also especially devoted to his students. In the case that a student or colleague came to him with a problem, he usually interrupted his work and focused all his attention to the problem. It frequently happened that he held discussions with students in front of the faculty even an hour or two after the end of his lectures.

Matjaž left behind a vast gap in the field of reactor physics in Slovenia. Fortunately he passed a lot of his knowledge to colleagues, which found their work also on this basis. An even larger gap is left behind him as a person.

Krško, November 2009

Igor LENGAR, Andrej PREDIN

Table of Contents /
Kazalo

Journal of Energy Technology

JET Volume 2 (2009), p.p. 13 - 20

Issue 4, November 2009

http://www.fe.uni-mb.si/si/e-jet/index.php

SINGLE-LAYER ORGANIC SEMICONDUCTOR SOLAR CELLS

SONČNE CELICE NA OSNOVI ENOPLASTNIH ORGANSKIH POLPREVODNIKOV

Bruno Cvikl [1]

Keywords: organic solar cell, excitons, electron trap density

Abstract

The physical processes occurring within a single-layer organic semiconductor solar cell under steady-state illumination leading to a short circuit current for the zero externally applied bias voltage are investigated. In the unipolar, single-layer metal/organic/metal structure, on account of the exponential decrease of light intensity within the organic material, the concentration of excitons is a function of the position within it. The charge recombination becomes spatially non-uniform, leading to the spatial dependent trap density. The short circuit current represents the uncompensated (by the built-in electric field separated) charges, which are, on the average, at most one exciton diffusion length away from the electrode. The model is applied to the hole-only single-layer poly(para-phenilene thienylene) organic solar cell ITO/LPPPT(59 nm)/Al published current-voltage data for which the spatial dependence of the internal potential, the resulting internal electric field, and the trap charge density is calculated.

Povzetek

V članku so modelirani fizikalni procesi za primer stacionarne osvetlitve sončne celice enoplastnega organskega polprevodnika, ki v odsotnosti zunanje napetosti vodijo do kratkostičnega toka. V unipolarni enoplastni kavina/organski polprevodnik/kovina strukturi, je zaradi eksponentnega pojemanja gostote toka svetlobe v plasti polprevodnika koncentracija ekscitonov funkcija globine. Gostota rekombinacij nabojev je zaradi zapisane lastnosti prostorsko odvisna kar povzroči globinsko porazdelitev gostote pasti. Kratkostični tok sestavljajo

[1] Prof. Bruno Cvikl, PhD., Faculty of Energy Technology, University of Maribor, Hočevarjev trg 1, 8270 Krško,Slovenia, and Jožef Štefan Institute, Jamova 39, 1000 Ljubljana, E-mail address: cvikl@uni-mb.si

----

nekompenzirani naboji prostorsko nagomilani (zaradi vgrajenega električnega polja) v povprečni oddaljenosti ene difuzijske dolžine ekscitona od electrode. Na osnovi v literaturi objavljenih meritev toka-napetosti enoplastne structure poli(para-fenilen thienilen)organske sončne celice ITO/LPPPT(59 nm)/Al je model uporabljen za izračun prostorske porazdelitve električnega potenciala, rezultirajočega notranjega električnega polja in koncentracije električno nabitih pasti v zapisanem organskem polprevodniku.

1 INTRODUCTION

It is a already well-established fact [1-3] that the light absorption by the organic species results primary in the production of *exciton* rather than free electron hole pairs. As known in the conventional inorganic solar cells, the photon absorption leads to the direct creation of the electron-hole pairs, which consequently diffuse through the bulk under the influence of the internal electric field towards the electrodes. In contrast, the operation of a polymer solar cell generally consists of various processes, of which the most important are the following: a) absorption of photons in the polymer resulting in the creation of an exciton (the electrically neutral bound hole-electron pair of typical radius 1 nm, and binding energy of about 0.25 eV [4, 5]), b) diffusion of the exciton towards the dissociation centers (defects, electrically charged traps, metal/organic interface, etc.), c) dissociation of the exciton that results in a bound electron-hole pair, d) to which follows either neutralization (i.e. the geminate recombination) of the electron-hole pairs, or in the presence of an electric field the dissociation of the bound pair into the separate free charges, e) after which the free charges under the influence of the internal electric field (if the external field is zero, the internal electric field is provided by the work function difference of the metal anode and the cathode) move towards their respected electrodes, and finally, f) the extraction of charge carriers by electrodes into the external circuit.

The power conversion efficiencies of today's solar cells are not yet high enough for these to be of any commercial interest. It has been established however that the conversion efficiency of the organic bilayer or multilayer structures are significantly larger than the one provided by the single-layer solar cell devices. In general, the very different generation, transport, and recombination processes, which occur in organic semiconductors, preclude the direct application of the simple charge generation models as developed for inorganic photovoltaic devices [6]. These processes are still not well understood, in spite of the fact that it has been well established that in case of single-layer devices the carrier generation occurs primarily at the electrodes [7], but at organic-organic interfaces in case of bi- or multilayers.

The observed photovoltaic properties of the single-layer solar cells are relatively scarce. Ghosh et al. [8] have developed the model of photovoltaic property of the single-layer organic structure in which the excitons are the major cause of the charge generation, transport, and surface dissociation for the case of unipolar charge carriers within the organic material, characterized by the absence of traps. The opposite case, i.e. the rigorous numerical investigation of the electrons and holes of non-equal mobilities under the applied electric field in the absence of traps, has been reported by Tessler et al. [9]. It appears that the problems of traps within the single-layer organic photovoltaic devices have received little attention, if any, thus far in spite of the fact that their effect on the I-V characteristics of the organic light emitting diodes is well documented [10, 11].

The present work is an attempt to address the role of charge traps and their immediate influence on the single-layer photovoltaic cells, where this effect might be of particular

----

relevance. In what follows it is assumed that within the organic charge transport gap the (shallow) single-energy traps level exists, which represent the major dissociation sites for excitons, which are generated by the incident light. Based upon this assumption, it will be shown that from the steady-state current-voltage measurements it is possible to elucidate the electrical characteristics of single-layer organic solar cells also for cases when the short-circuit photovoltaic current, I_{SC}, also consists of bipolar charge carriers. This statement will be illustrated on the room temperature I-V measurement of Klaus Petritsch [12]. As an example, the ITO/LPPPT(67 nm)/Al solar cell is analyzed, where LPPPT stands for the poly(para-phenilene thienylene), which is also interesting for fabrication of efficient organic multi-color LEDs and optically pumped blue solid state lasers [12]. In this respect, the following two characteristics points of his I-V data are of our interest: a) the short circuit current, I_{SC} = 1610 pA, and b) the open circuit voltage V_{OC} = 110 mV (when $I_{OC} \equiv 0$). The ITO/LPPPT /Al structure is the hole-only transporting medium [12]. One notes that the driving "force" for the first case is the so called built-in voltage, and in the second case an appropriate combination of the internal (photogeneration of carriers) and the externally generated bias voltage, V_a, are responsible for the charge drift.

2 THEORY

2.1 The short circuit current I_{SC} – the model of traps

The maximum current, I_{SC}, the solar cell is capable to produce under the steady state illuminating conditions occurs at short circuit, in which case the externally applied bias V_a = 0. In the literature, this case (of single-layer organic solar cell) is usually described in terms of the uniform built-in electric field defined as $E_{bi} = V_{bi}/L$. Here, V_{bi} is the built-in voltage defined as the difference of electrode work functions, and L is the thickness of the organic layer. On account of the internal built-in electric field, the charges generated under illumination are separated and move in the opposite directions towards the electrodes. These are considered to be blocking in the sense that they themselves generate negligible current but they can readily accept charges, i.e. photocurrents that come into contact with their surfaces. The first model, based upon the drift motion of charge carriers, for the description of the double extraction of *uniformly generated electron-hole pairs* from a photoconductor layer with non-injecting contacts has been suggested by Goodman and Rose [13].

The present work starts from the observation that, due to the absorption of light within the organic material, the generation of excitons is spatially nonuniform on the way from the transparent electrode further its inside. The excitons diffuse throughout the organic layer and eventually decay into the bound electron-hole pairs, which become separated under the influence of the built-in electric field and move towards their appropriate electrode. The average diffusion length of the free carriers are short on account of radiative and non-radiative recombination; consequently, in the first approximation, one may consider the free charges that are within the distance not greater than one diffusion length away from the electrodes. On account of the absorption of incident light, the exciton density at the transparent electrode interface is expected to exceed the exciton density close to the opposite electrode, and (after the exciton dissociation and generation of free charges) it is assumed that only those survive that are about the mean diffusion length from the electrodes. Within the organic bulk, the charge recombination occurs but, on account of the decreasing concentration of excitons away from the transparent electrode, the existing surplus charge of the identical sign become trapped, Fig. 1.

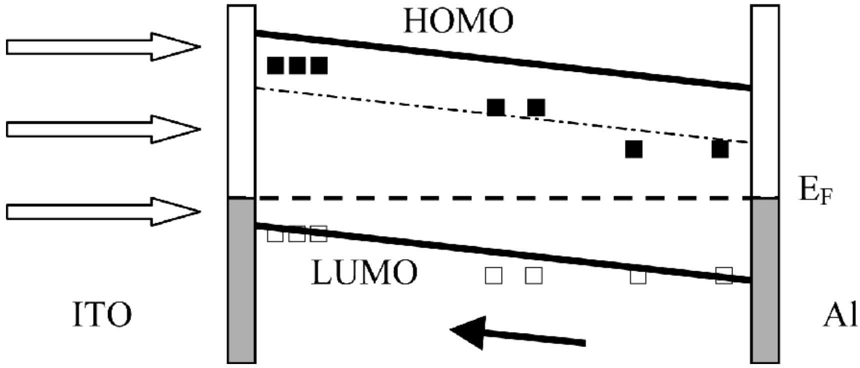


Figure 1: *Schematic presentation of the unipolar solar cell in the short circuit regime. Within the cell at zero external bias in the thermal equilibrium the Fermi levels of ITO (left) and Al (right) metal electrodes ought to coincide (dashed). Due to the different work functions of the metal electrodes, the spatial uniform internal electric field exists, which is directed (for external bias zero) towards left. The incident photons from the left are entering the organic layer in which their number on account of the light absorption is exponentially decreasing.*

In the steady state from the conservation of charge it follows that the flow of charges into the electrodes requires that the number of traps be continuously replenished. Thus in the steady state, one may assume [14] that the exciton density at the position x within the organic material is proportional to the absorbed incident light current density (i.e. flux) $j(x) = j_0 e^{-\alpha x}$ at this location. If

$$n(x) = \tau \eta N \alpha e^{-\alpha x} \qquad (2.1)$$

where n(x) is the *exciton density* at the position x within the organic, η is the quantum efficiency of exciton generation, N is the incident photon current density (number of photons per unit area per unit time), α is the absorption coefficient, and τ is an average lifetime between the generation of an exciton and charge trapping. Trapping occurs on account that not all exciton charges are fully recombined. The difference in the exciton density, dn, within the distance dx is obviously equal to $dn = -\tau \eta N \alpha^2 e^{-\alpha x} dx$ and this (according to the assumption above) is equal to an *increase* of the trap density dg equal to,

$$dg = \tau \eta N \alpha^2 e^{-\alpha x} \qquad (2.2)$$

The total difference of the trap density, g(x), throughout the organic is then,

$$g(x) = A(1-e^{-\alpha x}) \qquad (2.3)$$

since g(x=0) = 0, where the prefactor A is defined as,

$$A = \tau \eta N \alpha \qquad (2.4)$$

From the Eq. (2.3) one identifies the spatial dependence of the negatively charged trap density ρ(x) as,

----

$\rho(x) = - q\, g(x)$ (2.5)

so that the solution of the Poisson equation,

$$\frac{dE}{dx} = - \frac{qA}{\varepsilon\varepsilon_0}\left(1-e^{-\alpha x}\right) \qquad (2.6)$$

and the related expressions are [14],

$$E(0) = \frac{V_{bi}}{L} + \frac{G}{L}\left\{\frac{L^2}{2}+\frac{1}{\alpha}\left[\frac{1}{\alpha}\left(1-e^{-\alpha L}\right)-L\right]\right\} \qquad (2.7)$$

$$E(x) = E(0) - G\left(x+\frac{e^{-\alpha x}-1}{\alpha}\right) \qquad (2.8)$$

$$V(x) = V(0) - E(0)\,x + G\left\{\frac{x^2}{2}+\frac{1}{\alpha}\left[\frac{1}{\alpha}\left(1-e^{-\alpha x}\right)-x\right]\right\} \qquad (2.9)$$

where

$$G = \frac{\tau I_{SC}}{\varepsilon\varepsilon_0 S\left(L+\frac{e^{-\alpha L}-1}{\alpha}\right)} \qquad (2.10)$$

and the constant A is related to the short-circuit current, I_{SC}, through the relation,

$$A = \frac{\varepsilon\varepsilon_0}{q}\, G \qquad (2.11)$$

The above relations are based upon the assumption that the short circuit current in the steady state is given by,

$$I_{SC} = \frac{qN_{traps}}{\tau} \qquad (2.12)$$

where, N_{traps} denotes the total number of traps within the organic. Here, ε is the organic dielectric constant, S its lateral cross-section. The built-in voltage in the Eq. (7) is defined by the usual relation. The built in voltage is defined as $V_{bi} = [W_f(0) - W_f(L)]/q$, where W_f denotes the work function of the relevant metal electrode. In the derivation the reference frame is taken to point in the direction of the incident light with its origin placed at the metal/organic interface, i.e. ITO/LPPPT junction.

It is noted that in the steady state of charge generation, the internal electric field within the organic is, in general, spatially non-uniform. The intensity of the illumination and hence the generation of current is implicitly contained in the expression of I_{SC}, i.e. the directly measurable experimental quantity.

The absorption coefficient α = 0.015 nm^{-1}, S = 4 mm^2, ε = 3.5, I_{SC} = 1610 pA, L = 59 nm and for V_{bi} the value of - 0.5 V is taken [12], and if for τ the mean time between the exciton generation and formation of trap is approximately of the order of exciton life time, i.e. 1 x 10^{-6} s, the

----

expressions above contain no adjustable parameters. For these values of parameters, the potential difference ΔV = V(x) - V(0) is a linear decreasing function within LPPPT being zero at the origin and equal to -0.5 V at the LPPPT/Al interface. The corresponding internal electric field is equal to -8.47 x 10^6 V/m and it is constant. However, the trap density g(x) is a non linear function of the spatial coordinate with maximum at the LPPT/Al interface, Fig. 2.

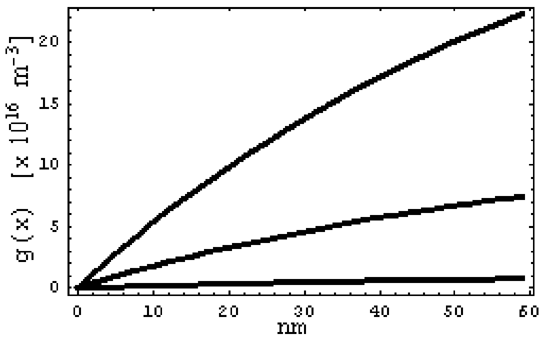


Figure 2: *The calculated spatial dependence of the electron trap density for the case of short circuit current at zero applied bias within the ITO/LPPPT(59 nm)/Al solar cell under the steady state illumination for τ = 0.1 x 10^{-6} s (bottom line), τ = 1. x 10^{-6} s (middle) and τ = 3. x 10^{-6} s (top line). The origin of a reference frame is at the ITO/LPPPT interface. The current-voltage data are taken from the ref. [12].*

2.2 The open circuit voltage, V_{OC}

For small values of positively biased external voltage, $V_{external}$ > 0, the electric current density is still in the direction of j_{SC}. At the externally applied bias equal to V_{OC}, the current density through the solar cell vanishes, j = 0, i.e. it is equal to zero. This signifies the fact that the total internal electric field, $E = - E_{bi} + E_{ext} = 0$ vanishes. Thus for $E_{ext} = E_{bi} = V_{bi}/L$, which occurs at V_{OC}, there is no current in the external circuit in spite of the fact that the incident light intensity remains unchanged. Within the organic, strong charge recombination is taking place in which the traps are also participating. The schematic view of the spatial dependence of the charge transport bands is for this case presented on Fig. 3.

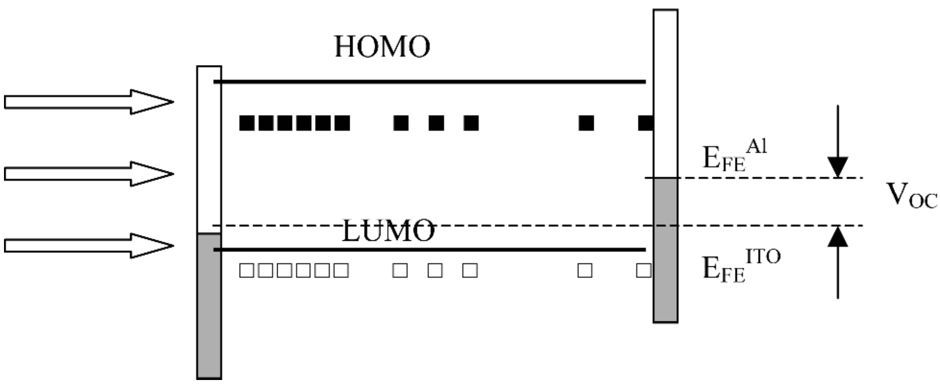


Figure 3: *Schematic representation of the energy transport bands for the applied bias equal to $V_a = V_{OC}$ at which the current within the organic is equal to zero. The steady state generation of neutral excitons by the incident light and their subsequent decay in separate charge carriers is followed by their steady state recombination in which the charge traps also participate.*

In the steady state of charge generation at the open circuit voltage V_{OC}, the total number of charged traps N_{traps} within the organic is then,

$$N_{traps} = S \tau^* \eta N \alpha \left(L + \frac{e^{-\alpha L} - 1}{\alpha} \right) \quad (2.13)$$

where τ^* now denotes the total time interval spanning the production of an exciton, its mean life time, and its decay followed by the charge recombination with trap.

For $V_a > V_{OC}$, the ITO electrode starts to inject the holes into organic semiconductor, which then drift and diffuse with an apparent mobility in the direction of the resultant internal electric field directed towards the right. The solar cell now essentially operates as a unipolar LED for which the spatial dependence of the internal electric field as well as the total (free and trapped) hole density may be analyzed along the steps described in references [11] and [15].

3 CONCLUSIONS

In this work, the physical processes occurring within the single-layer organic semiconductor solar cell leading to the short circuit current for the zero externally applied bias voltage are investigated. The absorption of photons within the organic primarily results in the creation of charge neutral excitons, which diffuse throughout the medium, are scattered, and followed by the exciton decay, due to the built-in internal electric field, into the spatially separated hole and an electron. In the unipolar, single-layer metal/organic/metal structure, on account of the exponential decrease of light intensity within the organic, the concentration of excitons is a function of the position within it. The charge recombination becomes spatially non-uniform, leading to the spatially dependent trap density. The short circuit current represents the uncompensated (by the built-in electric field separated) charges, which are, on the average, at most about one exciton diffusion length away from the electrode. The model is applied to the hole-only single-layer organic solar cell ITO/LPPPT(59 nm)/Al current-voltage data of K. Petritsch and it is shown that the internal potential and the resulting internal electric field, at $V_a = 0$, is a linear function of the spatial coordinate, but the electron trap density of the order of 10^{16} m^{-3} is slightly concave function of position from the ITO electrode towards the Al cathode.

References

[1] **P. Peumans, V. Bulovič, S. R. Forest**, Efficient photon harvesting at high optical intensities in ultrathin organic double-heterostructure photovoltaic diodes, Appl. Phys. Lett., **76**, 2650 (2000).

[2] **P. Peumans, A. Yakimov, S. R. Forrest**, Small molecular weight organic thin-film photodetectors and solar cells, J. Appl. Phys. **93**, 3693 (2003).

[3] **A. Kumar, S. Sista, Y. Yang**, Dipole induced anomalous S-shape I-V curves in polymer solar cells, J. Appl.Phys. **105**, 094512 (2009).

[4] **M. Pope and C. E. Swenberg**, *Electronic Processes in Organic Crystals and Polymers,* 2nd ed. (Oxford University Press, New York, 1999).

----

[5] **I. H. Campbell, T. W. Hagler, D. L. Smith, J. P. Ferraris**, Direct measurement of conjugated polymer electronic excitation energies using the metal/polymer/metal structures, Phys. Rev. Lett. **76**, 1900 (1996).

[6] **S. M. Sze**, *Physics of Semiconductor Devices,* 2nd Edition, John Wiley&Sons, New York, 1981.

[7] **G. G. Malliaras, J. R. Salem, P. J. Brock, J. C. Scott**, Photovoltaic measurements of the built-in potential in organic light emitting diodes and photodiodes, J. Appl. Phys. **84**, 1583 (1998).

[8] **A. K. Ghosh, T. Feng**, Merocyanine organic solar cells, J. Appl. Phys. **49**, 5982 (1978).

[9] **N. Tessler, N. Rappaport**, Excitation density dependence of photocurrent efficiency in low mobility semiconductors, J. Appl. Phys. **96**, 1083 (2004).

[10] **P. N. Murgatroyd**, Theory of space-charge-limited current enhanced by Frenkel effect, J. Phys. D; Appl. Phys., 151 (1970).

[11] **B. Cvikl**, The drift-diffusion interpretation of the electron current within the organic semiconductor characterized by the bulk single energy trap level, submitted for publication.

[12] **K. Petritsch** *in Organic Solar Cell Architectures*, PhD Thesis, 2000. Technisch-Naturwissenschaftliche Fakultät der Technischen Universität Graz, Austria.

[13] **M. Goodman, A. Rose**, Double extraction of uniformly generated electron-hole pairs from insulators with noninjecting contacts, J. Appl. Phys. **42**, 2823 (1971).

[14] **B. Cvikl**, unpublished.

[15] ref. /11/; see also **B. Cvikl, M. Koželj**, On the difference between drift and drift-diffusion interpretation of electron current in single-layer metal/organic semiconductor structure, 45th Int. conf. on microelectronics, devices and materials - MIDEM, Proceedings, September 9-11, 2009, p. 69-74, Postojna, Slovenia.

Journal of Energy Technology

JET Volume 2 (2009), p.p. 21 - 40

Issue 4, November 2009

http://www.fe.uni-mb.si/si/e-jet/index.php

ECONOMIC VIABILITY OF A NEW GAS-POWERED POWER STATION OR A NEW SOLID-FUEL POWER STATION ON THE SITE OF THERMO-PLANT TRBOVLJE

EKONOMSKA VARIABILNOST NOVE PLINSKE ELEKTRARNE NA TRDNA GORIVA TRBOVLJE

Alenka Kavkler[1], *Mejra Festić*[2]

Keywords: energy and electricity prices, environmental protection measures, cost efficiency of new technologies (**JEL: C22, C40, C50, Q31, Q40)**

Abstract

For an efficiency estimation of an investment in a gas-steam electric power station and a solid-fuel electric power station, we estimated the cost prices of electricity and two indicators of investment efficiency: internal rate of return and net present value. The risk of investment was estimated with sensitivity analysis. In this paper, we present three scenarios regarding the energy prices, fuel, the prices of emission coupons, capital costs and the selling price of electricity.

For the first scenario, we used the present market values of relevant variables. According to these suppositions, we confirmed that an investment in a gas-steam power station is acceptable, but risky. In contrast, an investment in a solid-fuel power station is not acceptable. Lower electricity prices are the main economic risk. The second scenario is based on the projections of energy prices and prices of emission coupons according to the projection of the

[1] Alenka Kavkler PhD., Faculty of Economics and Business, University of Maribor; EIPF - Economic Institute, Ljubljana. SLOVENIA. alenka.kavkler@uni-mb.si.

[2] Prof. Mejra Festić, PhD., Faculty of Economics and Business, University of Maribor; and EIPF - Economic Institute, Ljubljana. SLOVENIA. mejra.festic@uni-mb.si; mejra.festic@eipf.si; fax: 00386-2-250-8177.

“Long run energy balance of RS for the period 2006-2026,” prepared by the Jožef Štefan Institute. Under these circumstances, both projects are acceptable. The third scenario is prepared according to the forecasts of the “Annual Energy Outlook 2009 – Early Release Overview.” Under these circumstances, both projects could be acceptable but risky.

Povzetek

Za oceno učinkovitosti investicije v plinsko parno elektrarno ali v elektrarno na trda goriva smo izračunali lastno ceno električne energije ter dva kazalnika uspešnosti naložbe, namreč neto sedanjo vrednost ter interno stopnjo donosnosti. Tveganje investicije smo ocenili s pomočjo analize občutljivosti. Izdelali smo tri različne scenarije glede cen energentov, cene emisijskega kupona, stroškov kapitala ter prodajne cene elektrike

Za prvi scenarij smo uporabili trenutne vrednosti na trgu. Pri teh predpostavkah je investicija v plinsko parno elektrarno sprejemljiva, vendar tvegana, investicija v elektrarno na trda goriva pa ni sprejemljiva. Znižanje prodajne cene električne energije predstavlja najpomembnejše ekonomsko tveganje. Drugi scenarij temelji na projekcijah cen energentov ter cen emisijskih kuponov iz Dolgoročnih energetskih bilanc RS za obdobje 2006-2026, ki jih je pripravil Inštitut Jožef Štefan. V tem primeru sta investiciji v obe elektrarni sprejemljivi. Po kriteriju neto sedanje vrednosti, ki se uporablja kot odločitveni kriterij za medsebojno izključujoče projekte, je plinsko parna elektrarna ustreznejša izbira. Tretji scenarij je izdelan na osnovi napovedi iz »Annual Energy Outlook 2009 – Early Release Overview«. Investiciji v obe elektrarni sta sprejemljivi, vendar tvegani.

1 INTRODUCTION

The Trbovlje thermal power station (TET) has been operating under the conditions of priority dispatching since 2000 and uses domestic lignite from the Zasavje coal mines. The annual premium was set by the Government of the Republic of Slovenia and is related to the RTH Zasavje coal mines.

TET does not make any profit and has a 5 % share in the production of electricity in Slovenia. Considering the age of the TET thermal power station, the cost price of electricity is high, maintenance costs are increasing, and the environmental influence also affects TET's business activities. In addition, the plant's operational life (to be terminated in 2015) requires additional investments. By 2012, a new power plant should replace the existing one; TET has been operating for 40 years. This paper shows which available alternative technologies are economically viable. Below, three different scenarios are presented, regarding energy prices, emission coupon prices, cost of capital and the sale price of electricity for potential new technologies.

The value of investment in energetic infrastructure on the chosen existing locations of energy plants (including necessary costs for obtaining different licenses and permissions for building the energy power plant) is a strong argument, which proves the reasonableness and cost-effectiveness of keeping the existing locations with the introduction of alternative new technologies.

----

2 FINANCIAL ANALYSIS

2.1 Data and assumptions

Technical data about power stations, data about the investment costs and operational costs are taken from the Amended Investment Programmes, prepared by the company CEE Inženiring za energetiko in ekologijo (2008). In Table 1 and Table 2, only the most important data are presented for gas-powered power stations and for solid-fuel electric power stations. The gas-steam electric power station is to operate with a 60 % gas turbine load during the night and with a 100 % load during the day.

***Table 1:** Basic data for gas-powered power station*

GAS-STEAM ELECTRICITY POWER STATION	
Threshold power	281.8 MW
Life cycle	20 years
Investment value	EUR 267,242,000
Loan	EUR 127,442,700
Own resources	EUR 139,799,300
CO_2 emissions*	493,650 t/year
Natural gas consumption	262,000,000 Sm3/year
Electricity production	1,286,480 Mwh/year
Base load	983,800 Mwh/year
Peak load	302,800 Mwh/year

*Note: CO_2 emissions at full power operation amount to 591,761 t/year.

Source: CEE Inženiring za energetiko in ekologijo: Plinsko parna elektrarna TE Trbovlje, Novelirani investicijski program (Gas-steam Electric power station TE Trbovlje: Amended investment programme prepared by the CEE Inženiring za energetiko in ekologijo company)

A gas-steam electric power station can produce 24 % peak load and 76 % base load energy. The same amount of peak load energy produced was presumed for a solid-fuel electric power station. A normalised investment amount, expressed in EUR per kW of power, amounts to 948.38 EUR/kW for a gas-steam electric power station and 2202.36 EUR/kW for a solid-fuel electric power station. In the study "Projected Costs of Generating Electricity, 2005 Update," published by the Nuclear Energy Agency, the International Energy Agency and OECD, which includes data on approximately 130 electricity power stations from more than 20 countries, the normalised investment value for a solid-fuel electric power station (1000-1500 USD/kW or 741-1111 EUR/kW) is approximately twice as high as for a gas-steam power station (400-800 USD/kW or 296-592 EUR/kW). It must be taken into account that the life cycle of a solid-fuel power plant is 40 years, whereas the life cycle for a gas-steam power plant is only 20 years.

Table 2: *Basic data for solid-fuel electric power station*

SOLID-FUEL ELECTRIC POWER STATION	
Threshold power	206.9 MW
Life cycle	40 years
Investment value	EUR 455,771,000
Loan	EUR 218,520,000
Own resources	EUR 237,251,000
CO_2 emissions	892,797 t/year
Coal consumption	1,010,342 t/year
Electricity production	1,324,094 Mwh/year

Source: CEE Inženiring za energetiko in ekologijo: Izgradnja enote na trda goriva, Novelirani investicijski program (Solid-fuel electric power station: Amended investment programme prepared by the company CEE Inženiring za energetiko in ekologijo)

The cost of capital is given in Table 3. When determining the cost of ownership capital, the capital asset pricing model (CAPM) was used. The required profitability of individual investments consists of risk-free rate of return and an additional premium for risks, which is multiplied with the coefficient beta (Berk et al., 2004):

$$R = RFr + RPm \cdot \beta \qquad (2.1)$$

For the risk-free rate (RFr) we used present value for 3-month Euribor (in February 2009). As it was estimated that the investment risk is below the average, β has value 0.8. The market risk premium (RPm) is determined on the basis of the difference between expected average rate of return of the Slovenian Stock Market Index (SBI20) and a risk-free interest rate. The cost of ownership capital thus amounts to 5.88 %. Because it is expected that TET will be given a favourable loan for its investment, a low interest rate for the loan was assumed (rd=4.5 %), whereas the influence of a higher interest rate was assessed with sensitivity analysis. When determining the cost of debt capital, it is necessary to take into account tax on profit, which amounts to 20 % (T). Cost of debt capital is calculated as $rd \cdot (1-T)$ and amounts to 3.6 %. The share of ownership capital is the same for both power stations; thus the weighted average cost of capital (WACC) coincides (4.78 %).

Table 3: *Cost of capital*

COST OF CAPITAL	
Cost of debt capital	3.6 %
rd	4.5 %
T	20 %
Cost of ownership capital*	5.88 %
RFr	1.88 %
RPm	5 %
β	0.8
WACC	4.78 %
Share of debt capital	48 %
Share of ownership capital	52 %

* Note: In the amended investment programmes, prepared by the CEE, cost of ownership capital was not taken into account.

2.2 Methodology

In order to assess investment efficiency, the cost price of electricity and two investment effectiveness indicators were calculated, i.e. net present value and internal rate of return. The investment risk was calculated by means of sensitivity analysis.

2.1.1 Own cost of electricity

If total cost is divided by annual electrical production, we obtain the specific total cost or own cost of produced electricity. The real own cost of electricity can be determined only for the past on the basis of costs in the accounting statement and usually changes during the investment depreciation period. The future price when planning new plants is calculated on the basis of the present value of the own cost of electricity. In this calculation, the specific cost of capital and depreciation are combined in specific permanent investment costs as an instalment of total investment capital, which will be depreciated (Tuma and Sekavčnik, 2004).

2.1.2 Dynamic methods and investment effectiveness indicators

Dynamic methods for determining the effectiveness of investment projects take into account investment costs and profits during the whole operational life of the investment. In practice, two dynamic methods for investment effectiveness indicators are most frequently used. By using the method of **net present value (NPV)**, the present (discounted) value of an expected investment cost is deducted from the present value of expected profits. By the profit during a certain year, we mean the so-called net money flow. The choice of discount rate depends on

----

sources for financing the investment. For the discount rate, we use the weighted average cost of capital (Berk et al., 2004). When the investment is financed with debt capital, the cost of capital is presented by interest rates and cost of obtaining the loan, which are both included in the effective interest rate for the loan. If the company finances an investment with its own resources, the discount rate is represented by the opportunity cost of its own money or such rate of return that would be reached with the best investment possibility (Filipič and Mlinarič, 1999).

An important dynamic method for assessing the investment effectiveness is the **internal rate of return (IRR)**, which is defined as a discount rate, in which the net present value of investment equals zero. In other words, the net present value of investment costs equals net present value of expected profits.

The analysis of financial flows was carried out by taking into account the guidelines from the Priročnik za izdelavo analize stroškov in koristi investicijskih projektov (Guidelines for the Analysis of Costs and Profits of Investment Projects), prepared by the evaluation department of the Directorate-general for Regional Policy of the European Commission. Net financial flow is defined as the difference between total revenue and total expenditure, where revenue is profit from sales, and expenditure is cost of operation and investment costs.

In calculating tax on profit, expenditure also includes depreciation and interest rates for the loan. A 20 % tax rate was used, because the power station will begin to operate after 2010. In accordance with the Corporate Income Tax Act (ZDDPO-2), which was adopted on January 1, 2007, a tax loss of an ongoing tax period can be covered by reducing the tax base during the next periods without any time limit, which has been taken into account when calculating dynamic effectiveness indicators.

2.1.3 Sensitivity analysis

We were not familiar with exact investment flows, because they are prone to several risks; therefore, they can merely be evaluated. With the sensitivity analysis we determine how changes in certain variables affect the level of investment flows and, subsequently, influence investment effectiveness indicators. Each time, we only change one variable by presuming that the values of other variables remain unchanged. It is important to determine critical variables that influence the most on the net present value and internal rate of return (Brigham and Houston, 2001).

2.1.4 Investment effectiveness indicators and sensitivity analysis

Below are three different scenarios with regard to the price of energy products, emission coupons, cost of capital and selling price of electricity; these are the factors that will influence the effectiveness of the investment. In all three scenarios, we assumed that free CO_2 quotas will be suspended after 2012.

2.1.5 Scenario 1

For the first scenario, present market values were used. In determining the price of emission coupons and the price of gas, we took into account the present data from the "European Energy

----

Exchange" and standardised futures contracts until 2012. The selling price of base load and peak load electricity was determined on the basis of internal assessments of HSE and TET for 2009, while the price of coal was taken from the amended investment plan. The share of produced peak load electricity in the amended investment plan for the solid-fuel electric power station was not given; therefore, the same share was used as in the case of the gas-steam electric power station (24 %). In the amended investment programme for the solid-fuel electric power station, the selling price of electricity is determined so that the project reaches at least a 7 % internal rate of return. Such an assumption is not reasonable, because in this case the net present value is always positive.

Table 4: *Assumptions for Scenario 1*

ASSUMPTIONS FOR SCENARIO 1	
Price of emission coupons	11.85 EUR/t
Price of natural gas	0.22 EUR/Sm^3
Price of coal	58.2 EUR/t
Selling price of base load electricity	72.6 EUR/MWh
Selling price of peak load electricity	100.8 EUR/MWh
Average selling price of electricity	79.4 EUR/MWh

The own cost of produced electricity, net present value (NPV) and internal rate of return (IRR) for the investment in a gas-steam electric power station and a solid-fuel electric power station are shown in Table 5. The own cost of electricity produced in gas-steam electricity power plant amounts to 74.62 EUR/MWh and is lower than the assumed selling price. The discount rate in calculating net present value is the same as weighted average cost of capital (WACC). Thus, the gas-steam electric power station is a viable project, because the net present value is positive and the internal rate of return is higher than the cost of capital. In contrast, the investment in the solid-fuel electric power station is not viable, which was confirmed by all three indicators.

Table 5: *Investment effectiveness indicators for Scenario 1*

THE ASSESSMENT OF INVESTMENT EFFECTIVENESS		
	Gas-steam electricity power station	Solid-fuel electric power station
Own cost	74.62 EUR/MWh	84.38 EUR/MWh
NPV	EUR 39.15 mio	EUR -88.25 mio
IRR	6.74 %	2.91 %

A sensitivity analysis was carried out for a gas-steam electricity power station. The following changes have been taken into account:

- A decrease of the selling price of electricity and the price of gas by 10 % and 20 % and an increase by 10 %, 20 % and 30 %,
- A decrease of the effective interest rate for the loan to 4 % and an increase to 5 %, 5.5 %, 6.5 %, or 7.5 %,
- A decrease in the price of CO_2 coupons to 10 EUR and an increase of this price to 20, 25, 30 and 35 EUR.

As seen from Table 6, which presents the results of sensitivity analysis, the investment in a gas-steam electric power station is also risky. In three out of four changed parameters, the net present value can be negative, and the internal rate of return can be lower than cost of capital. Both investment effectiveness indicators are therefore sensitive to changes in chosen variables. A reduction in the selling price of electricity represents the most important economic risk for the investment in a gas-steam electric power station with the given assumptions. With a 20 % decrease of electricity, the internal rate of return is not positive or is not defined. The results of the sensitivity analysis with regard to electricity price and the price of natural gas are also given in Picture 1, and with regard to interest rates in Picture 2. The change in interest rates does not have a substantial influence on net present value of the investment.

Table 6: *Sensitivity analysis for gas-steam electric power station in Scenario 1*

PRICE OF ELECTRICITY						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	-138.20	-42.74	39.15	121.05	202.95	284.84
IRR (%)	-	2.39	6.74	10.35	13.53	16.44
PRICE OF GAS						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	131.75	85.45	39.15	-7.14	-53.46	-107.08
IRR (%)	10.78	8.85	6.74	4.41	1.73	-
INTEREST RATE FOR THE LOAN						
	4 %		5 %	5.5 %	6.5 %	7.5 %
NPV (mio EUR)	43.13	39.15	35.34	31.68	24.80	18.46
IRR (%)	6.71	6.74	6.78	6.82	6.90	6.98
PRICE OF EMISSION COUPONS						
	10 EUR		20 EUR	25 EUR	30 EUR	35 EUR
NPV (mio EUR)	46.49	39.15	6.84	-12.99	-32.82	-52.65
IRR (%)	7.09	6.74	5.15	4.10	2.98	1.78

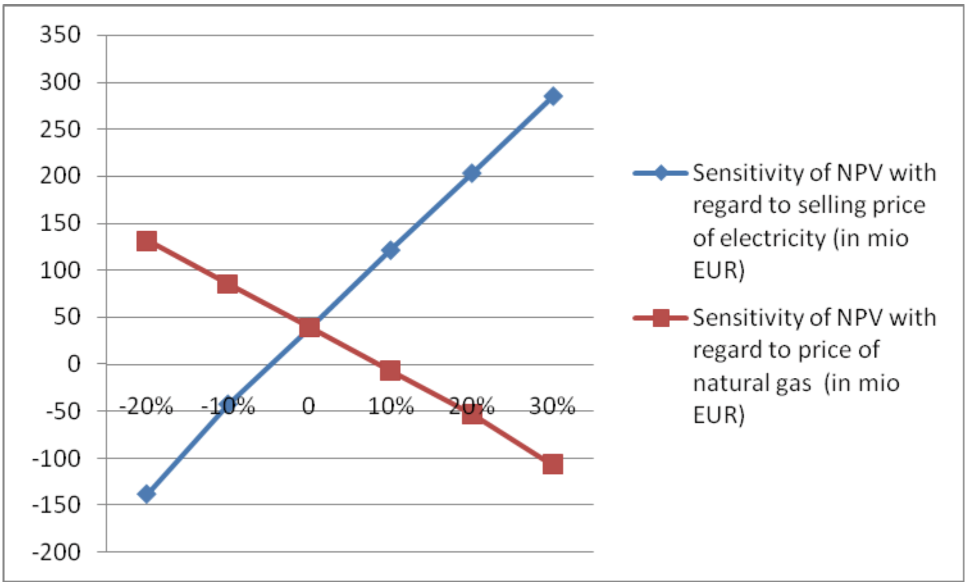


Figure 1: *Sensitivity analysis with regard to the selling price of electricity and the price of natural gas*

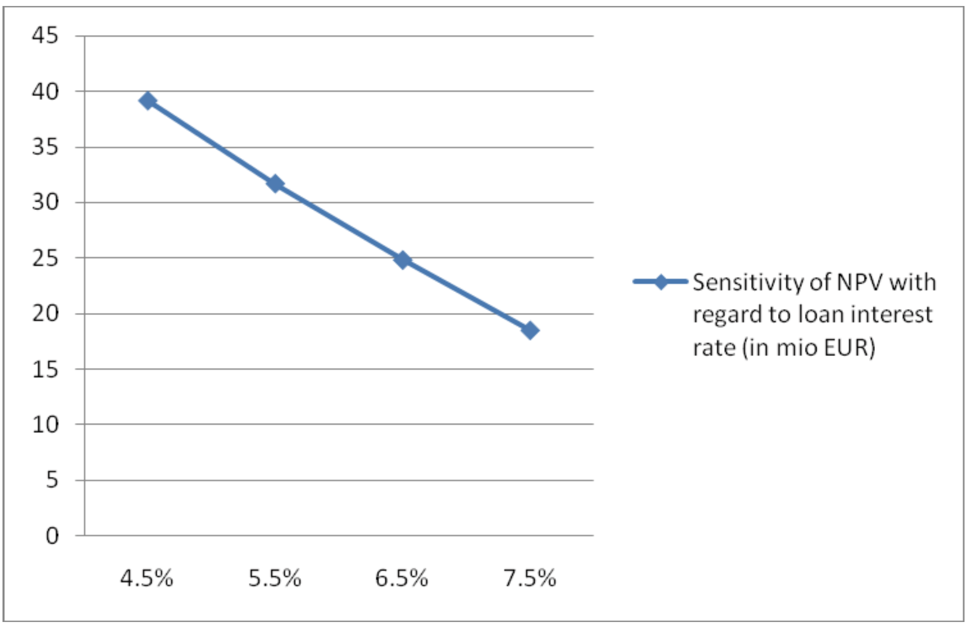


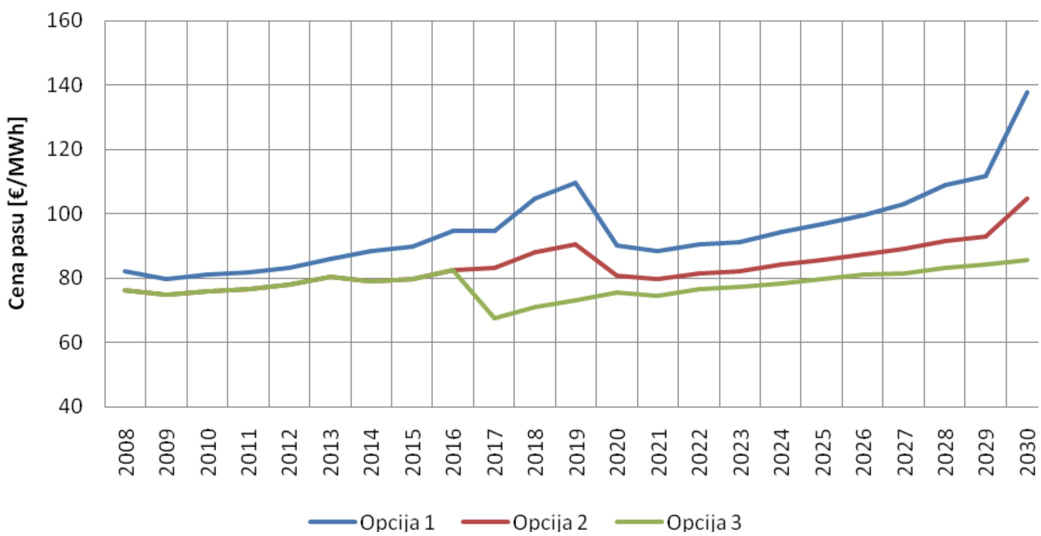
Figure 2: *Sensitivity analysis with regard to the interest rates on the loan*

2.1.5 Scenario 2

Scenario 2 is based on projections of energy prices and the price of emission coupons from the "Long-term Energy Balance of the RS for the 2006-2026 period," prepared by the Center za energetsko učinkovitost Instituta Jozef Stefan (Centre for Energy efficiency at the Jozef Stefan Institute) for the Ministry of the Economy. Three options are described in the study:

- Option 1 (reference scenario):
  This option presupposes only minor investments, e.g. a new gas turbine TEŠ 5, the building of TEŠ 6 and TE-TOL 1;
- Option 2 (balanced scenario):
  This option also takes into account TE-TOL 2, new gas electricity power stations, with a number of locations for building (e.g. Kidričevo, Sermin, Trbovlje), PPE Brestanica and ČHE Kozjak;
- Option 3 (NEK 2 and TEŠ 6 scenario):
  This option takes into account NEK 2 with 1000 MW of installed power.

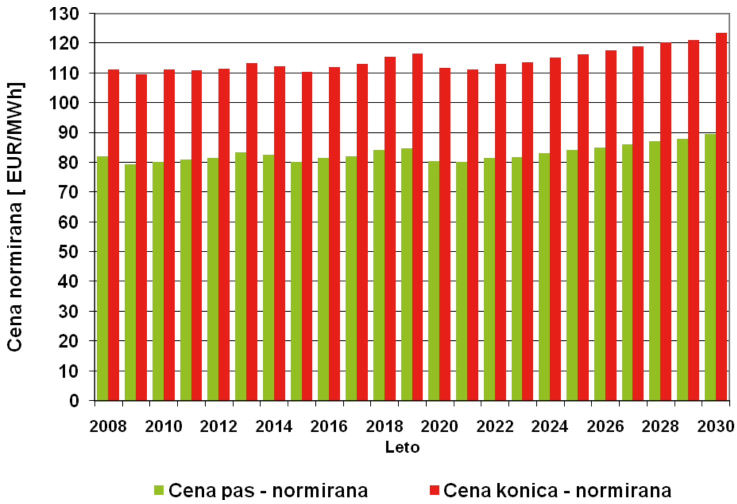
There are two possibilities described in each of the three options with regard to the economic development (a 1.5 % consumption growth for the first option, a 3 % consumption growth for the second option), and two possibilities regarding effective use of energy and renewable energy resources (RES); i.e. intensive consumption of RES and reference consumption of RES. Picture 3 shows the base load price for all options, assuming a 3 % consumption growth.



Source: Long-term energy balance in the RS for the 2006-2026 period (reproduced by permission of the authors at the Centre for Energy Efficiency at the Jozef Stefan Institute)

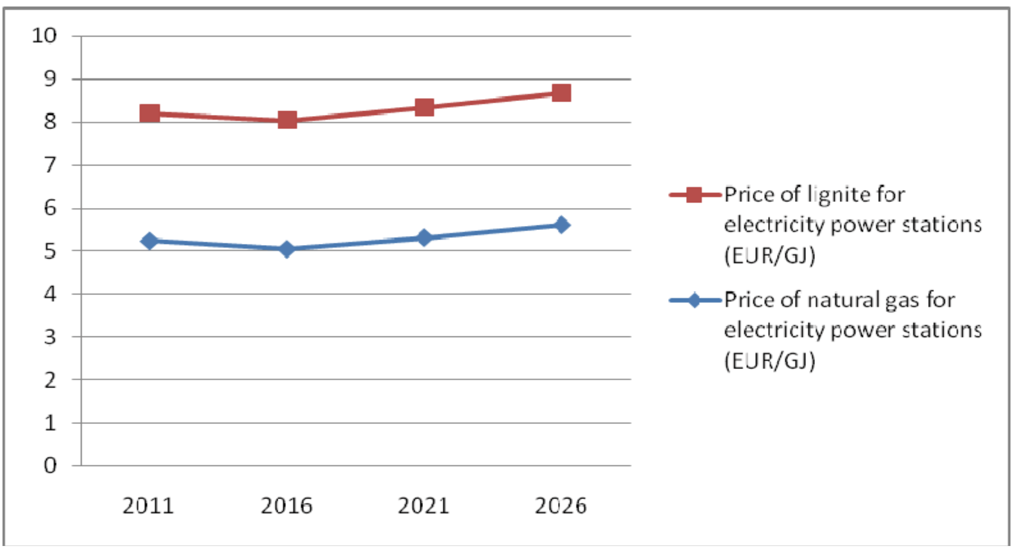
Figure 3: *The base load price for Options 1 (in blue), 2 (in red) and 3 (in green) with a 3 % consumption growth*

For Scenario 2, we used simulated data for the normalised base load price and normalised price of peak load by taking into account the 2nd option (balanced scenario), a 3 % consumption growth and reference consumption of RES. The data is shown on Picture 4. For the period from 2015 to 2030, the base load price is on average approximately 83 EUR/MWh; the price of peak load is 114 EUR/MWh.



Source: Long-term energy balance in the RS for the 2006-2026 period (reproduced by permission of the authors at the Centre for Energy Efficiency at the Jozef Stefan Institute).

Figure 4: *Normalised base load price (in green) and normalised price of peak load (in red) at a 3 % consumption growth and reference consumption of RES*



Source of data: Long-term energy balance in the RS for the 2006-2026 period

Figure 5: *Price projections for natural gas and lignite for electricity power stations*

According to the “Long-term energy balance in the RS for the 2006-2026 period” the price of emission coupons in the period between 2013 and 2030 is 25 EUR/t. For the price of natural gas, we used the forecast value for electric power plants in 2021 (5.31 EUR/GJ); for the price of coal, we used the price of lignite for electric power plants in 2021 (3.03 EUR/GJ). Projections of prices for both energy products are given for years 2011, 2016, 2021 and 2026 (Picture 5); the value for 2021 is an approximation of the average for the period from 2016 to 2026.

Assumptions for Scenario 2 are shown in Table 7.

Table 7: *Assumptions for Scenario 2*

ASSUMPTIONS FOR SCENARIO 2	
Price of emission coupons	25 EUR/t
Price of natural gas	0.201 EUR/Sm3 (5.31 EUR/GJ)
Price of coal	42.68 EUR/t (3.03 EUR/GJ)
Selling price of base load electricity	83 EUR/MWh
Selling price of peak load electricity	114 EUR/MWh
Average selling price of electricity	90.44 EUR/MWh

The own cost of electricity is lower for both electricity power stations than the assumed selling price. The net present value is positive, while the internal rate of return is higher than the cost of capital (Table 8), which means that investment in both electricity power stations is viable. In mutually exclusive projects, the best decisive criterion is net present value, because the use of internal rate or return can cause certain difficulties due to the different scope of investment and a different timing of financial flows (Brigham and Houston, 2001; Berk et al., 2004). In Scenario 2, a gas-steam electric power station is again a better choice than a solid-fuel electric power station.

Table 8: *Investment effectiveness indicators for Scenario 2*

THE ASSESSMENT OF INVESTMENT EFFECTIVENESS		
	Gas-steam electricity power station	Solid-fuel electric power station
Own cost	74.75 EUR/MWh	81.41 EUR/MWh
NPV	EUR 141.21 mio	EUR 110.96 mio
IRR	11.16 %	6.78 %

In sensitivity analysis, the following changes have been taken into account for both electric power stations:

- A decrease of the selling price of electricity and the price of gas or coal by 10 %

----

and 20 % and an increase by 10 %, 20 % and 30 %,

- A decrease of the effective interest rate for the loan to 4 % and an increase to 5 %, 5.5 %, 6.5 %, or 7.5 %,
- A decrease in the price of CO_2 coupons to 15 EUR and 20 EUR and an increase of this price to 30, 35 and 40 EUR.

The results of the sensitivity analysis for gas-steam electric power stations (Table 9) and solid-fuel electric power station (Table 10) show that investment in gas-steam electric power stations is less risky than the investment in solid-fuel electric power stations. For gas-steam power stations, the net present value is negative only if the selling price of electricity lowers by 20 %. However, the net present value is calculated with all other parameters remaining unchanged. Such an assumption is not reasonable, because a reduction in the price of electricity would also lead to a reduction in the price of natural gas, which would, consequently, increase the net present value.

Table 9: *Sensitivity analysis for the gas-steam electric power station for Scenario 2*

PRICE OF ELECTRICITY						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	-45.47	47.89	141.21	234.52	327.84	421.16
IRR (%)	2.23	7.15	11.16	14.68	17.89	20.88
PRICE OF NATURAL GAS						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	225.81	183.51	141.21	98.91	56.60	14.30
IRR (%)	14.37	12.81	11.16	9.42	7.56	5.53
INTEREST RATES FOR THE LOAN						
	4 %		5 %	5.5 %	6.5 %	7.5 %
NPV (mio EUR)	147.82	141.21	134.84	128.70	117.09	106.31
IRR (%)	11.13	11.16	11.20	11.23	11.31	11.38
PRICE OF EMISSION COUPONS						
	15 EUR	20 EUR		30 EUR	35 EUR	40 EUR
NPV (mio EUR)	180.86	161.03	141.21	121.38	101.55	81.73
IRR (%)	12.71	11.94	11.16	10.36	9.54	8.68

Table 10: *Sensitivity analysis for solid-fuel electric power stations for Scenario 2*

PRICE OF ELECTRICITY						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	-149.99	-17.01	110.96	238.91	366.86	494.81
IRR (%)	-	4.45	6.78	8.80	10.63	12.32
PRICE OF COAL						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	203.11	157.04	110.96	64.89	18.82	-27.29
IRR (%)	8.26	7.54	6.78	5.99	5.15	4.24
INTEREST RATES FOR THE LOAN						
	4 %		5 %	5.5 %	6.5 %	7.5 %
NPV (mio EUR)	124.15	110.96	98.53	86.81	65.32	46.16
IRR (%)	6.76	6.78	6.81	6.83	6.88	6.93
PRICE OF EMISSION COUPONS						
	15 EUR	20 EUR		30 EUR	35 EUR	40 EUR
NPV (mio EUR)	206.36	158.66	110.96	63.27	15.57	-32.16
IRR (%)	8.31	7.56	6.78	5.96	5.08	4.14

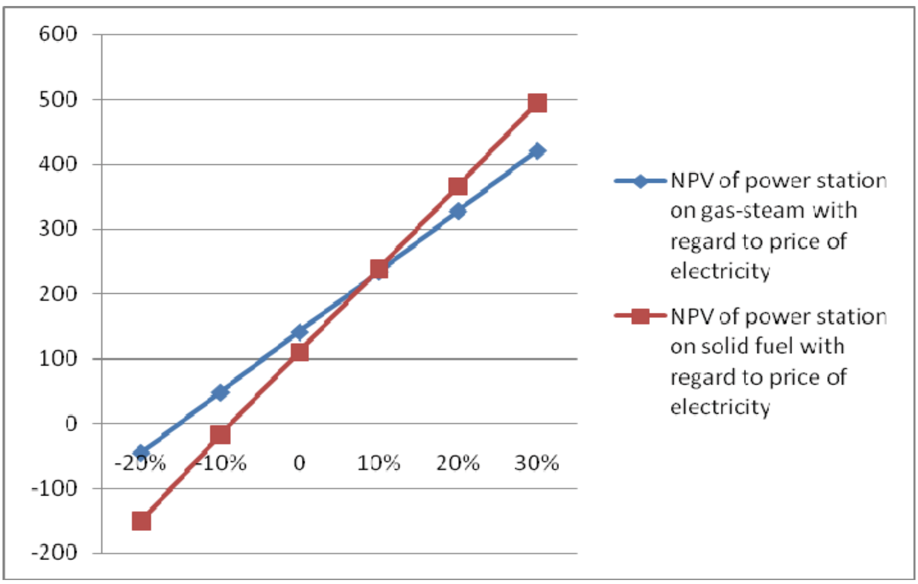


Figure 6: *Sensitivity to the selling price of electricity*

The results of sensitivity analysis for the price of electricity and the price of fuel are presented on Pictures 6 and 7. Solid-fuel electric power stations are more sensitive to changes in both input parameters, as shown by the angle of the line segments. The difference is substantial, especially in the change of electricity selling price. It can also be seen that for an increase of electricity price by 20 %, a solid-fuel electric power station would be a more suitable choice than a gas-steam electric power station, because it has a higher net present value.

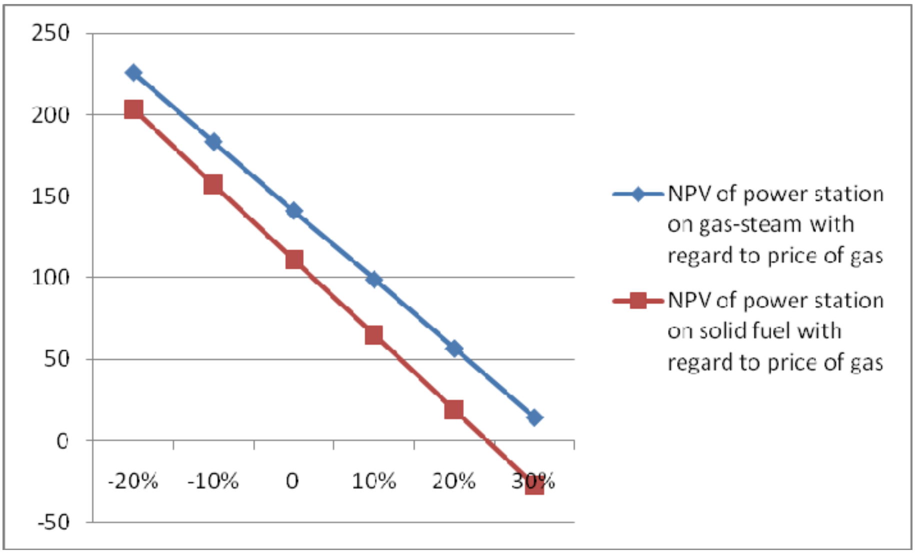
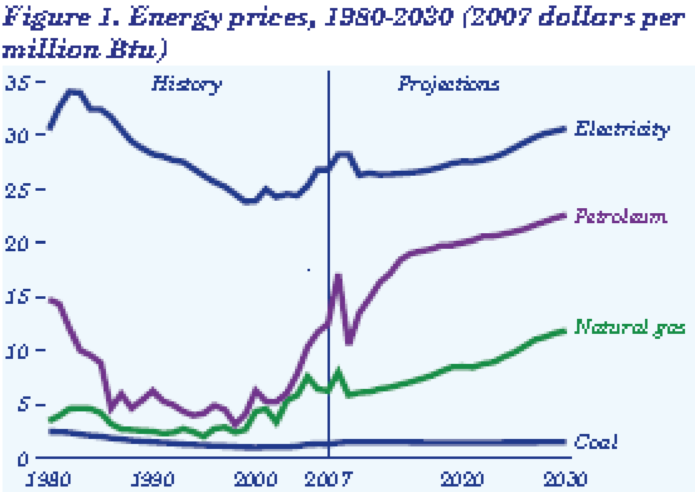


Figure 7: Sensitivity to the price of fuel

2.1.6 Scenario 3

The third scenario is based on the forecast in the "Annual Energy Outlook 2009 – Early Release Overview," which is published by the Energy Information Administration, which also prepares official statistics in the field of energy for the US government. According to the forecast in the "Annual Energy Outlook 2009," the price of natural gas will stagnate until 2011, then start to increase until 2020 (Picture 8). In 2021, the price of natural gas will slightly fall, and then gradually increase until 2030. It is expected that the price of coal in the observed period will not change considerably. The price of electricity will be increasing during the whole period, but slower than the price of natural gas. Macroeconomic and political factors are taken into account when calculating the forecast.



Source: Annual Energy Outlook 2009-Early release overview, Energy information administration (2009).

Figure 8: *Energy products price forecast from the "Annual Energy Outlook"*

We assumed in Scenario 3 that the price of coal will stagnate, and that the price of natural gas will increase by 1.76 % annually. Similarly, the price of electricity will increase by 1.02 % annually. Both assumptions are based on the average annual growth from the "Annual Energy Outlook 2009" in the period between 2010 and 2030. The starting prices for energy products are present prices or prices from Scenario 1.

Table 11: *Assumptions for Scenario 3*

ASSUMPTIONS FOR SCENARIO 3	
Price of emission coupons	11.85 EUR/t
Price of coal	58.2 EUR/t
Initial price of natural gas	0.22 EUR/Sm^3
Annual growth level of natural gas price	1.76 %
Initial selling price of electricity	
base load	72.6 EUR/MWh
peak load	100.8 EUR/MWh
Annual growth level of electricity price	1.02%

The net present value is positive for both investments; the internal rate of return is higher than the weighted average cost of capital (Table 12). Thus, in Scenario 3 investment in both electricity power stations is reasonable. In accordance with the net present value criterion (for excluding projects), we would choose a solid-fuel electric power station.

Table 12: *Investment effectiveness indicators for Scenario 3*

THE ASSESSMENT OF INVESTMENT EFFECTIVENESS		
	Gas-steam electric power station	Solid-fuel electrical power station
Own cost	88.02 EUR/MWh	84.38 EUR/MWh
NPV	EUR 37.93 mio	EUR 75.46 mio
IRR	6.69 %	5.90 %

Sensitivity analysis was carried out using the same changes as in Scenario 2. The results are given in Tables 13 and 14. Both investments are risky.

Table 13: *Sensitivity analysis for the gas-steam electric power station for Scenario 3*

PRICE OF ELECTRICITY						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	-157.33	-51.01	37.93	126.87	215.81	304.75
IRR (%)	-	1.81	6.69	10.55	13.88	16.88
PRICE OF NATURAL GAS						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	144.86	91.40	37.93	-15.53	-69.10	-135.48
IRR (%)	11.20	9.07	6.69	3.94	0.51	-
INTEREST RATE FOR THE LOAN						
	4 %		5 %	5.5 %	6.5 %	7.5 %
NPV (mio EUR)	41.86	37.93	34.17	30.55	23.76	17.51
IRR (%)	6.66	6.69	6.73	6.77	6.85	6.93
EMMISION COUPON PRICE						
	10 EUR		20 EUR	25 EUR	30 EUR	35 EUR
NPV (mio EUR)	45.27	37.93	5.61	-14.21	-34.04	-53.87
IRR (%)	7.04	6.69	5.08	4.02	2.90	1.69

Table 14: *Sensitivity analysis for solid-fuel electric power station for Scenario 3*

PRICE OF ELECTRICITY						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	-197.65	-57.03	75.46	204.14	332.52	460.89
IRR (%)	-	3.89	5.90	7.64	9.23	10.73
PRICE OF NATURAL GAS						
	-20 %	-10 %		+10 %	+20 %	+30 %
NPV (mio EUR)	201.43	138.57	75.46	11.20	-54.87	-123.16
IRR (%)	7.65	6.79	5.90	4.95	3.95	-
INTEREST RATE FOR THE LOAN						
	4 %		5 %	5.5 %	6.5 %	7.5 %
NPV (mio EUR)	90.38	75.46	61.44	48.26	24.18	2.83
IRR (%)	5.88	5.90	5.91	5.93	5.96	5.99
EMISSION COUPON PRICE						
	10 EUR		20 EUR	25 EUR	30 EUR	35 EUR
NPV (mio EUR)	93.260	75.46	-4.31	-54.64	-106.29	-159.04
IRR (%)	6.15	5.90	4.72	3.95	-	-

3 CONCLUSIONS

It can be concluded that Scenario 2 is the best for our study, because it is based on projections for the 2006–2026 period, which focused on the Slovenian market. According to this scenario, a gas-steam electric power station is a viable investment with a low risk.

References

[1] *Annual energy outlook 2008*, Energy information administration, 2008.
[2] *Annual energy outlook 2009-Early release overview*, Energy information administration, 2009.
A. Berk, I. Lončarski, P. Zajc: *Poslovne finance*, Ljubljana: Ekonomska fakulteta, 2004.
[3] E. Brigham, J.F. Houston: *Fundamentals of financial management*, Harcourt College Publishers: Orlando, 2001.
[4] CEE Inženiring za energetiko in ekologijo: *Izgradnja enote na trda goriva, Novelirani investicijski program*, Ljubljana: CEE, december 2008.
[5] CEE Inženiring za energetiko in ekologijo: *Plinsko parna elektrarna TE Trbovlje, Novelirani investicijski program*, Ljubljana: CEE, oktober 2008.

----

[6] D. Filipič, F. Mlinarič: *Temelji poslovnih financ*, Maribor: Ekonomsko-poslovna fakulteta, 1999.

[7] Institut Jozef Stefan, Center za energetsko učinkovitost: *Dolgoročne energetske bilance RS za obdobje 2006-2026, 1. in 2. del*, Ljubljana: IJS, 2008.

[8] *Priročnik za izdelavo analize stroškov in koristi investicijskih projektov*, izdelano za ocenjevalni oddelek Generalnega direktorata za regionalno politiko pri Evropski komisiji, dostopno na spletnem naslovu http://euskladi.gov.si/skladi/3dok/dn6024.pdf, 2004.

[9] *Projected costs of generating electricity, 2005 Update*, Nuclear energy agency, International energy agency in OECD, 2005.

[10] M. Tuma, M. Sekavčnik: *Energetski sistemi: preskrba z električno energijo in toploto*, Ljubljana: Fakulteta za strojništvo, 2004.

Journal of Energy Technology

JET Volume 2 (2009), p.p. 41 - 50

Issue 4, November 2009

http://www.fe.uni-mb.si/si/e-jet/index.php

NUCLEAR DESIGN CALCULATIONS OF THE NPP KRŠKO CORE

NEVTRONSKI PROJEKTNI IZRAČUNI SREDICE NUKLEARNE ELEKTRARNE KRŠKO

Marjan Kromar[1], Andrej Trkov[2]

Keywords: nuclear reactor, nuclear core design, nuclear calculation, PWR

Abstract

Nuclear design calculations of the NPP Krško core performed at the Jožef Stefan Institute are presented in this paper. The CORD-2 system, developed by the Reactor Physics Department, is intended for core design calculations of pressurized water reactors. It enables the determination of the core reactivity and power distribution. The software has been validated for the nuclear design calculations of PWR cores and has been used for the verification of the NPP Krško reload cores since 1990. The main components and the calculational methods of the CORD-2 system are briefly described in this paper.

Povzetek

Predstavljeni so nevtronski projektni izračuni sredice reaktorja Nuklearne elektrarne Krško, ki se izvajajo na Institutu Jožef Stefan. Sistem CORD-2, razvit na Odseku za reaktorsko fiziko, je namenjen projektnim izračunom sredice tlačnovodnih reaktorjev. Omogoča določitev reaktivnosti in porazdelitve moči po sredici. Veljavnost rezultatov paketa je bila potrjena na projektnih izračunih tlačnovodnih reaktorjev. Sistem CORD-2 se uporablja za preverjanje projektnih izračunov sredice Nuklearne elektrarne Krško od leta 1990. V prispevku so opisane glavne komponente sistema in uporabljene matematične metode.

[1] Marjan Kromar, PhD., Tel.: +386 1 588 5292, Fax: +386 1 588 5377, Jožef Stefan Institute, Reactor Physics Department, Jamova 39, 1001 Ljubljana, Slovenia, E-mail: marjan.kromar@ijs.si

[2] Andrej Trkov, PhD., Tel.: +386 1 588 5324, Fax: +386 1 588 5377, Jožef Stefan Institute, Reactor Physics Department, Jamova 39, 1001 Ljubljana, Slovenia, E-mail: andrej.trkov@ijs.si

----

1 INTRODUCTION

Reactor core calculations are of interest to nuclear designers, power reactor utilities and to national nuclear regulatory authorities. Their purpose is to assure safe, reliable and economical reactor operation. The Jožef Stefan Institute has been providing technical support services to the Krško Nuclear Power Plant (NPP) and to the national nuclear regulatory authority for more than 25 years, since the first cycle of the plant's operation. To perform this task, it was necessary to develop computational tools for reactor core calculations. A number of software packages for such purposes exist, but they are commercial or proprietary.

The CORD-2 system [1] developed by the Reactor Physics Department of the Jožef Stefan Institute is intended for core design calculations of pressurised water reactors (PWR's). The main goal in assembling the CORD-2 core design system was to provide a non-commercial package that could be used for simple fast calculations (such as those frequently required for fuel management) as well as for accurate calculations (for example, core design after refuelling).

2 NUCLEAR DESIGN CALCULATIONS

The parameters appearing in a nuclear core design can be obtained from a series of calculations for the effective multiplication factor k_{eff} and the power distribution at different core configurations and operating conditions. From these basic parameters, all other required quantities, such as reactivity coefficients, control rod worth, power peaking factors, etc., can be determined. All these parameters are needed if we want to achieve the two main goals of nuclear design calculations:

1. Determination of core nuclear properties that enables safe planning and control of the reactor behaviour inside technical specification limitations.
2. Optimization of the core loading pattern that enables good fuel utilization and economical plant operation.

Despite rapid computer development in recent years, core calculations based on the Monte Carlo approach are still not fast enough for the series of calculations needed for typical reload core design. Therefore, deterministic methods have to be applied in the solution of neutron transport and diffusion equation. The CORD-2 system consists of two basic reactor physics codes: WIMS-D [2] and GNOMER [3]. WIMS-D is a well-known and widely-used lattice code. Version WIMS-D5 is available from the NEA Data Bank in Paris. GNOMER solves the neutron diffusion equation in three-dimensional Cartesian geometry by **G**reen's function **NO**dal **ME**thod [4]. It also includes advanced features for cross-section homogenization and a simple thermohydraulics module from the CTEMP [5] code, so that thermal feedback can be taken into account.

3 CORD-2 SYSTEM

The geometry of the reactor core is too complex to be solved in one step. In Figure 1, the NPP Krško core is presented. The core consists of 121 fuel assemblies. Each assembly has 235 fuel rods arranged in the 16×16 array. The remaining 21 positions are intended for control rods and the central instrumentation channel.

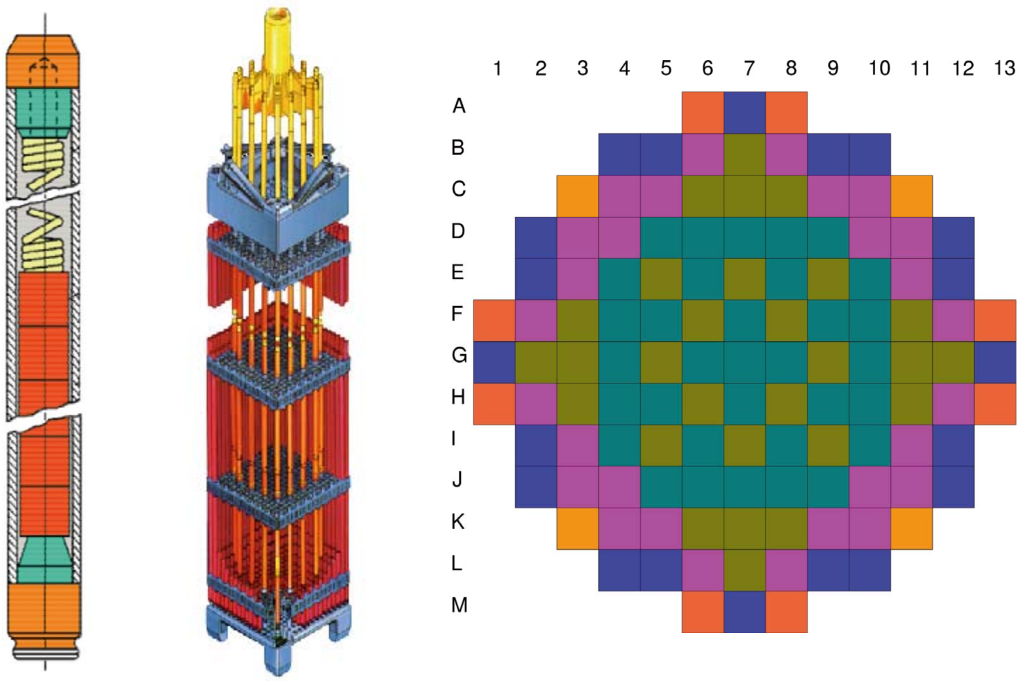


Figure 1: *Fuel rod, fuel assembly and reactor core of the NPP Krško*

A solution for the whole core in 3-D geometry is sought in several steps. On the reactor lattice level, transport methods are applied. From the solution, cell-homogenized few-group cross sections are obtained. These are used in the calculations for a fuel assembly flux distribution, where it was found that the solution in the few-group diffusion approximation is adequate. From the solution, assembly-homogenized effective two-group cross sections can be defined, which are suitable for solving the diffusion equation for the whole core by a coarse mesh nodal method.

3.1 Lattice cell homogenization

To homogenize a reactor lattice cell with WIMS-D, an array of 3×3 lattice cells is considered. The geometry is shown schematically in Figure 2, where the detailed internal structure of cells has been omitted for clarity. The outer cells (f) always contain fuel, while the central cell (x) may contain a fuel pin, a water hole, a burnable poison pin or another type of special cell. With a fuel cell in the centre, an extra layer of water is added on the outside of the cell array to preserve the total fuel assembly moderator-to-fuel ratio.

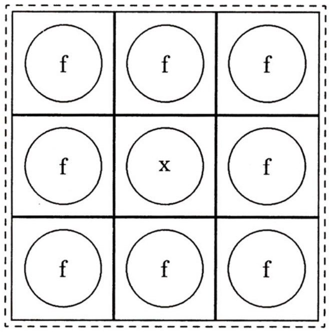


Figure 2: *Lattice cell array configuration (schematic drawing)*

A solution for the array of cells is obtained using WIMS-D. A spectrox calculation is performed on 69 energy groups (average effective cell), resulting in the condensation of the neutron cross sections to the 32 groups. These cross sections are used in the transport calculation of the whole supercell (Figure 2). From the obtained results, the cell-homogenized 10-group cross sections are derived for the central cell only. The effective diffusion homogenization method (EDH) is used [6], which guarantees not only reaction rate conservation, but also the conservation of partial currents on the boundary of an equivalent homogeneous cell in the diffusion approximation.

3.2 Fuel assembly calculations

An array of homogeneous cells that constitute a fuel assembly is considered (Figure 3). Most of the cells contain fuel, but there are some which contain only guide tubes filled with water or other inserts, such as control rods or burnable poison rods.

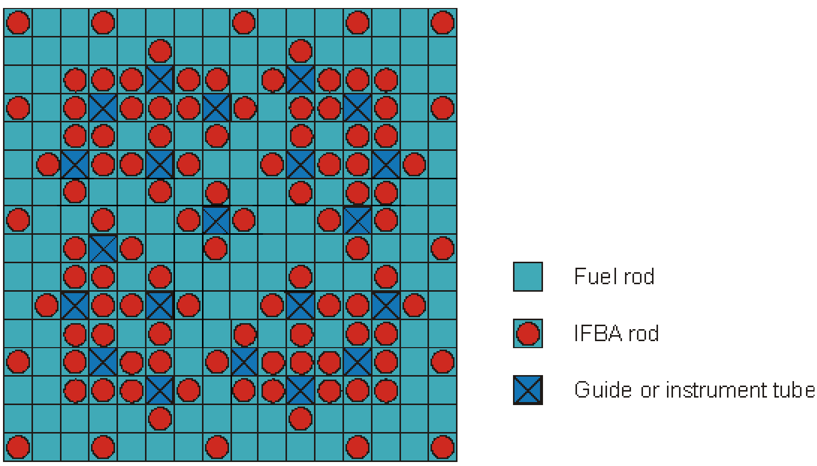


Figure 3: Fuel assembly

To obtain the neutron flux distribution over the domain of a fuel assembly, transport methods are frequently applied. A detailed whole assembly treatment in a transport approximation is appropriate if a suitable code for the calculation is available, and if execution times are

----

acceptable. However, when cell homogenization needs to be performed, the additional error introduced due to the use of the diffusion approximation is minimal, provided that suitable cell homogenization methods are applied and that a sufficient number of energy groups are used. In CORD-2, the solution over the domain of a fuel assembly is obtained in the diffusion approximation using GNOMER in 10 energy groups. The pin power distribution is used to generate the form-factors in the process of reconstructing the heterogeneous assembly and global core pin power distribution.

The fuel assembly surroundings affect the flux distribution and hence the homogenized assembly cross sections. Critical core conditions, for which k_{eff}=1 are usually of interest; therefore, a critical albedo search is performed when seeking the solution over the domain of the fuel assembly. Although such treatment is approximate and ignores the specific properties of the neighbouring fuel assemblies, it nevertheless correctly represents the assembly surroundings in an average sense. It is considered superior to the critical buckling search that is commonly applied, because it treats the radial leakage explicitly and correctly at least on average, while the critical buckling approach is approximately valid only to model the axial leakage.

The results of the calculation are assembly-homogenized two-group cross sections. As in the lattice cell case, the EDH method for homogenization is used. The calculation is repeated for each axial region of an assembly, for all assemblies in the core, considering core symmetries, if any.

3.3 Global core calculations

The calculation to determine the global core power distribution and the excess reactivity is the last step in the sequence. The solution is obtained with GNOMER in two energy groups and on a coarse mesh that usually corresponds to one node per assembly and ten regions in the core axial direction, with two additional regions for the axial reflector. Such geometrical representation is adequate for the unrodded core; however, when control rods are partly inserted, a denser axial mesh is recommended. A uniform mesh of 24 axial regions is convenient.

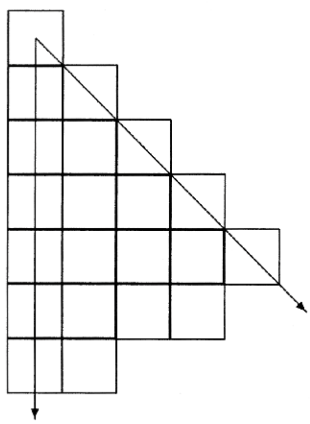


Figure 4: *Octant of the NPP Krško core*

To obtain detailed pin-by-pin power distribution, a nodal solution for the homogeneous nodes has to be modulated with form factors obtained in the fuel assembly homogenization process. An applied EDH method with the critical albedo search considers correct assembly boundary condition in an average sense for approximately critical cores.

3.4 Thermohydraulic feedback

The cross sections for the core operating at power should be generated, taking into account the actual (critical) boron concentration, and corresponding temperature distributions of the fuel and moderator. However, these depend on the power distribution that we are trying to calculate. An iterative procedure is required. Due to the complex nature of the thermohydraulic feedback effects and because the flux distributions are sensitive to small perturbations, approximately ten iterations are necessary.

To calculate the cross sections rigorously through WIMS-D is very computationally intensive and time consuming. Alternatively, a rough but very simple method of modifying the cross sections by the reactivity coefficient method [7] is available in GNOMER. Starting from a given cross-section set, generated with WIMS-D (at hot-zero-power condition, say) and modified through the reactivity coefficient method in GNOMER, the power and temperature distributions as well as the critical boron concentration at desired conditions are calculated. The results are used to approximately define the conditions at which the cross sections are recalculated rigorously with WIMS-D. When calculating the core power distribution with these cross sections, the required modifications by the reactivity coefficient method are much smaller. In fact, they are so small that further iteration is seldom necessary.

3.5 Fuel material burnup

The treatment of burnup in CORD-2 differs from the approach commonly adopted in other code systems, where burnup-dependent cross sections are parameterized. In CORD-2, a library of isotopic composition vectors, ISOlib, is constructed as a function of average fuel assembly operating conditions. An isotopic composition vector gives the masses (in grams) of all isotopes in the WIMS-D library per ton of heavy metal in fresh fuel. An axial section of a fuel assembly is assumed to have operated at constant, average operating conditions. An isotopic composition vector that corresponds to such conditions is retrieved from the ISOlib library by interpolation and is used to prepare input for WIMS-D to calculate cross sections. At present, the parameters for tabulating the ISOlib library are:

- fuel assembly type,
- enrichment,
- moderator density,
- fuel temperature,
- average boron concentration during burnup,
- average number of inserts during burnup.

----

4 RESULTS

The CORD-2 system has been validated against the experimental data of NPP Krško and the Almaraz benchmark [8]. Comparison has shown that CORD-2 system is sufficiently accurate in predicting the parameters that are required to ensure the safe operation of nuclear power plants. In Figures 5 and 6, a typical calculated power distribution of the NPP Krško is presented.

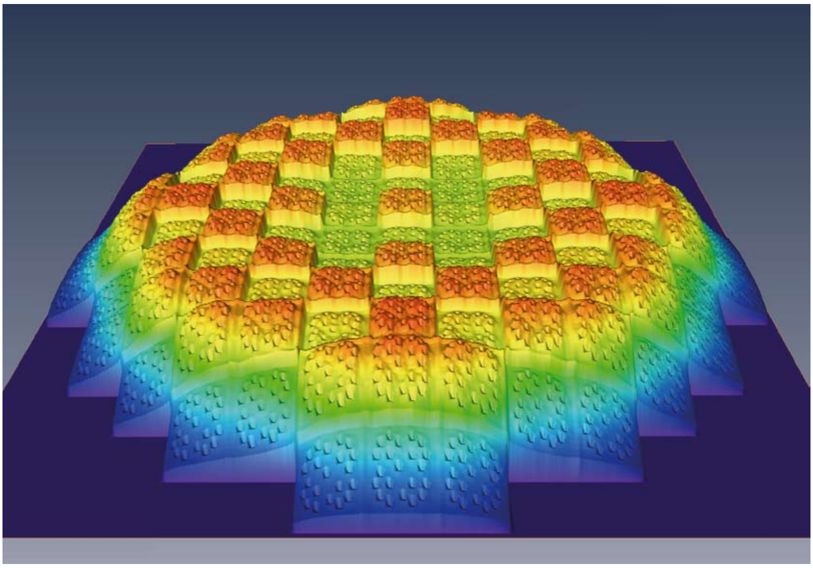


Figure 5: *Radial power distribution*

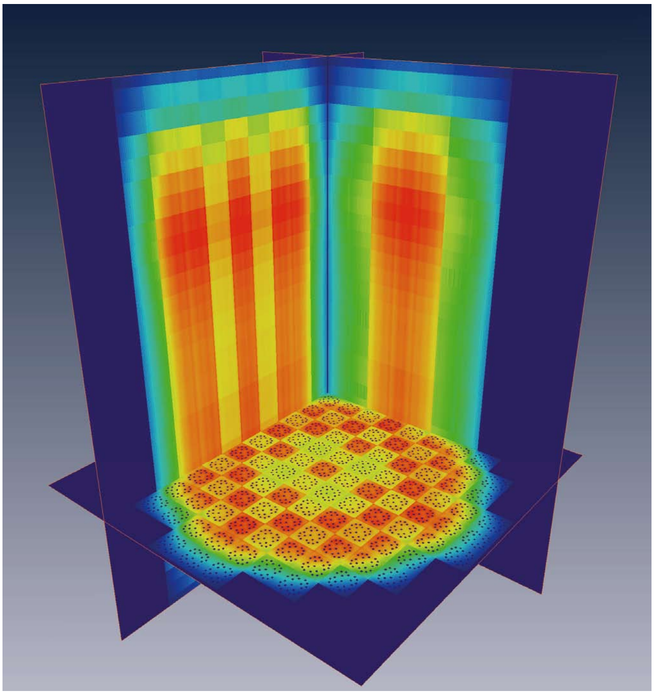


Figure 6: *Power distribution at different core cross sections*

For each reload cycle at least the following items are determined:

- Core Depletion
  - Core power distribution
  - Core power peaking factors
  - Fuel burnup
  - Critical boron concentrations
- Reactivity Parameters
  - Reactivity coefficients
  - Reactivity defects
- Reactivity Control
  - Minimum required shutdown boron concentrations
  - Control rod worth
  - Shutdown margin
- Startup Parameters
  - Delayed neutron data
  - Reactivity parameters needed to perform startup tests

Some typical examples of the calculated parameters from the core depletion and the reactivity parameters section are presented in Figures 7 and 8.

5 SUMMARY

Nuclear design calculations of the NPP Krško core performed at the Jožef Stefan Institute are presented. The calculations are executed with the CORD-2 system developed by the Reactor Physics Department. The system has been validated for the design calculations of PWR cores. The main calculation steps are:

- Lattice-cell multigroup transport solution and cell cross-section homogenization by the EDH method,
- fuel assembly few-group diffusion solution with a critical albedo search and assembly cross section homogenization by the EDH method,
- global-core, two-group, coarse-mesh, three-dimensional diffusion solution with the Green's function nodal method to obtain the effective multiplication factor and the power distribution,
- reconstruction of the neutron flux and power distribution within homogenized nodes.

In addition, some special features of the calculational steps with reference to CORD-2 were discussed, including the treatment of thermohydraulic feedback and burnup.

----

0 MWD/MTU
2462 ppm
1.418 PEAK $F_{\Delta H}$

25B 1.361 1.418 0 * 0	24B 1.231 1.290 23805 0	25A 1.303 1.353 0 0	24A 1.167 1.211 26921 0	25B 1.321 1.387 0 0	25B 1.068 1.313 0 0	23B 0.364 0.617 37636 0
24B 1.231 1.291 23805 0	24B 1.166 1.219 28051 0	24A 1.161 1.221 26119 0	25A 1.336 1.388 0 0	24B 1.231 1.321 21003 0	25B 1.045 1.327 0 0	23B 0.305 0.623 34634 0
25A 1.303 1.354 0 0	24A 1.185 1.251 24331 0	25A 1.350 1.410 0 0	24B 1.299 1.360 21714 0	25B 1.226 1.410 0 0	24A 0.589 0.967 26618 0	
24A 1.167 1.210 26921 0	25A 1.342 1.395 0 0	24B 1.301 1.363 21689 0	25A 1.275 1.388 0 0	25B 1.068 1.380 0 0	24A 0.359 0.748 27237 0	
25B 1.321 1.387 0 0	24B 1.227 1.321 21213 0	25B 1.224 1.410 0 0	25B 1.067 1.379 0 0	23A 0.416 0.851 35912 0		
25B 1.068 1.313 0 0	25B 1.041 1.326 0 0	24A 0.582 0.960 27323 0	24A 0.358 0.745 27248 0			
23B 0.364 0.617 37636 0	23B 0.303 0.620 34761 0					

RE	
AP	AVERAGE POWER
MP	ASSEMBLY $F_{\Delta H}$
AB	AVERAGE BURNUP
CB	CYCLE BURNUP

RE INDICATES REGION
* INDICATES ASSEMBLY OF PEAK

Figure 7: *Example of core depletion parameters*

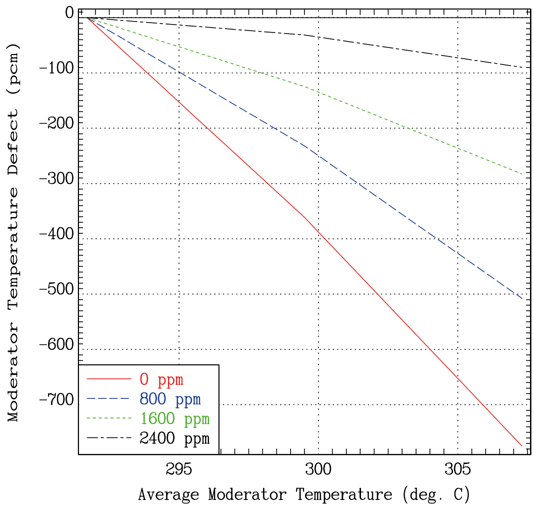


Figure 8: *Example of moderator temperature defect calculated at different boron concentrations*

References

[1] **A. Trkov, M. Ravnik:** *CORD-2 Package for PWR Nuclear Core Design Calculations,* Proceedings of the International Conference on Reactor Physics and Reactor computations, Tel-Aviv, 23-26. Jan. 1994, Beer-Sheva, Ben-Gurion University of the Negev Press, (1994).

[2] **J. R. Askew, F. J. Fayers, P. B. Kemshell:** *A General Description of the Code WIMS,* J. Br. Nucl. Energy Soc., **5**, p. 564, (1966).

[3] **A. Trkov:** *GNOMER - Multigroup 3-Dimensional Neutron Diffusion Nodal Code,* Institute Jožef Stefan, Ljubljana, Slovenia, IJS-DP-6688, March 1993.

[4] **A. Trkov, M. Najžer, L. Škerget:** *Variant of Green's Function Nodal Method for Neutron Diffusion,* J. Nucl. Sci. Technol., **27**, 8, pp. 766-777, (1990).

[5] **M. Kromar, S. Slavič, A. Trkov:** *CTEMP: A Code for Thermohydraulic Calculations,* Institute Jožef Stefan, Ljubljana, Slovenia, IJS-DP-6143, February 1991.

[6] **A. Trkov, M. Ravnik:** *Effective Diffusion Homogenization of Cross Sections for Pressurized Water Reactor Core Calculations,* Nucl. Sci. Enging., **116**, 2, pp. 86-95, (1994).

[7] **M. Kromar, A. Trkov:** *Simulation of the power feedback effects with the reactivity coefficient method,* V: PHYSOR 2000, Proceedings, Pittsburgh: American Nuclear Society, (2000).

[8] **M. J. Crijns (Scientific secretary):** *In-Core Fuel Management Code Package Validation for PWR's,* Coordinated research project, International Atomic Energy Agency, Vienna, IAEA-TECDOC-815, August 1995.

Journal of Energy Technology

JET Volume 2 (2009), p.p. 51 - 60

Issue 4, November 2009

http://www.fe.uni-mb.si/si/e-jet/index.php

DEEP REPOSITORY FOR SPENT NUCLEAR FUEL

TRAJNO ODLAGALIŠČE ZA IZRABLJENO JEDRSKO GORIVO

G. Žerovnik[ℜ], L. Snoj[1], M. Ravnik[2], M. Kromar[3]

Keywords: spent nuclear fuel, deep repository, decay heat, optimization

Abstract

In spite of the possibility of fuel reprocessing, direct spent nuclear fuel disposal is still a viable option in Slovenia. The current strategy regarded by Slovenian Agency for Radwaste Management is terminal disposal in deep repository. Due to decay heat release, spent nuclear fuel interacts with the repository site and the surrounding rock. Arrangement of spent fuel in the repository according to its decay heat was demonstrated for the case of the Krško Nuclear Power Plant.

Povzetek

Kljub možnosti reprocesiranja goriva je možnost direktnega trajnega odlaganja izrabljenega jedrskega goriva v Sloveniji še vedno aktualna. Trenutna strategija Agencije za radioaktivne odpadke je trajno odlaganje v globinskem odlagališču. Zaradi oddajanja razpadne toplote izrabljeno gorivo interagira z okoliško kamnino v in okoli odlagališča. Metoda razporejanja izrabljenega jedrskega goriva v globinskem odlagališču je bila demonstrirana na primeru Jedrske elektrarne Krško.

[ℜ] Corresponding author: Gašper Žerovnik, Jožef Stefan Institute, Tel.: +386 1 588 5326, Fax: +386 1 588 5454, Mailing address: Jamova cesta 39, 1000 Ljubljana, E-mail address: gasper.zerovnik@ijs.si

[1] Luka Snoj, Jožef Stefan Institute, E-mail address: luka.snoj@ijs.si

[2] Matjaž Ravnik, Jožef Stefan Institute, E-mail address: matjaz.ravnik@ijs.si

[3] Marjan Kromar, Jožef Stefan Institute, E-mail address: marjan.kromar@ijs.si

----

1 INTRODUCTION

Amongst other possibilities (especially reprocessing) in spent nuclear fuel (SNF) management, the Krško Nuclear Power Plant (NPP) decommissioning program [1] has adopted direct disposal. The Swedish concept of deep repository in hard rock [2] is considered. In the reference design for PWR SNF, spent fuel assemblies (SFA) are filled into metal canisters which are placed within the rock (Figure 1). After irradiation in the NPP, the SNF emits large amounts of thermal power (the so-called decay heat – a consequence of nuclear fission and neutron activation products radioactive decay) and has to be actively cooled in the spent fuel storage pool for several years before terminal disposal in a deep rock repository. Otherwise, the structural firmness of the rock can be compromised by overheating.

This restriction requires as uniform as possible arrangement of SFAs in canisters according to their decay heat. Also, it implies the need of interim storage active cooling period before terminal disposal. This paper examines the problems of SNF decay heat and arrangement optimization.

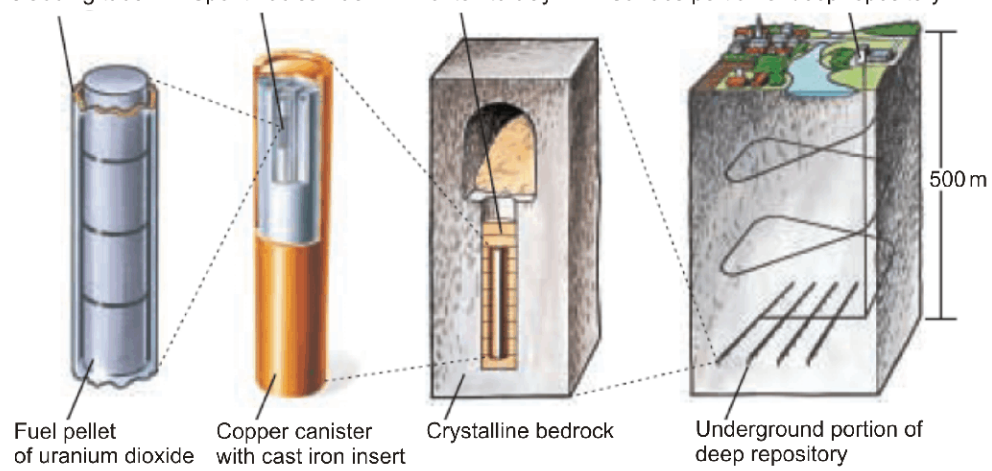


Figure 1: *Schematics of deep repository for spent nuclear fuel [2].*

2 NUCLEAR FUEL

Nuclear fuel in NPP Krško is in the form of uranium dioxide pellets, which are inserted in a fuel cladding made of a zirconium alloy [3]. The NPP Krško fuel assembly (Figure 2) has 16 × 16 (256) positions for fuel pins, control rods, and instrumentation rods. Typical dimensions of a PWR fuel assembly are 20 cm × 20 cm × 400 cm. In NPP Krško, the reactor core consists of 121 fuel assemblies, amounting to a total of approximately 50 t of uranium. The content of the fissile isotope ^{235}U (uranium enrichment) varies from 2 % to 5 %. From the first NPP Krško fuel cycle until 2004, the plant operated mainly on 12-month fuel cycles, until further it will operate on 18-month cycles. In the most recent cycles 55 out of 121 fuel assemblies, on average, are substituted during a NPP outage.

Figure 2: *Typical pressurized water reactor (PWR) spent fuel assembly.*

During operation of the NPP, fuel and structural components are irradiated by neutrons to form fission and activation products, respectively. The number density of absorbed neutrons is measured by fuel burnup that is defined as the total heat released by fissions in unit mass of uranium [MWd/tU]. Both fission and activation products are mostly highly radioactive isotopes with an excess of neutrons. Because of numerous active isotopes, the consequential decay heat is a complex function of burnup, irradiation and cooling time ([4], Figure 3).

Since neutron flux is a function of position in the reactor core, the spent fuel burnup varies from one SFA to another. The biggest differences in decay heat, however, arise between SFAs irradiated in various NPP fuel cycles – because of differences in cooling times (Figure 3). The resulting typical probability density of spent fuel assemblies over power (decay heat) becomes a relatively broad distribution (Figure 4).

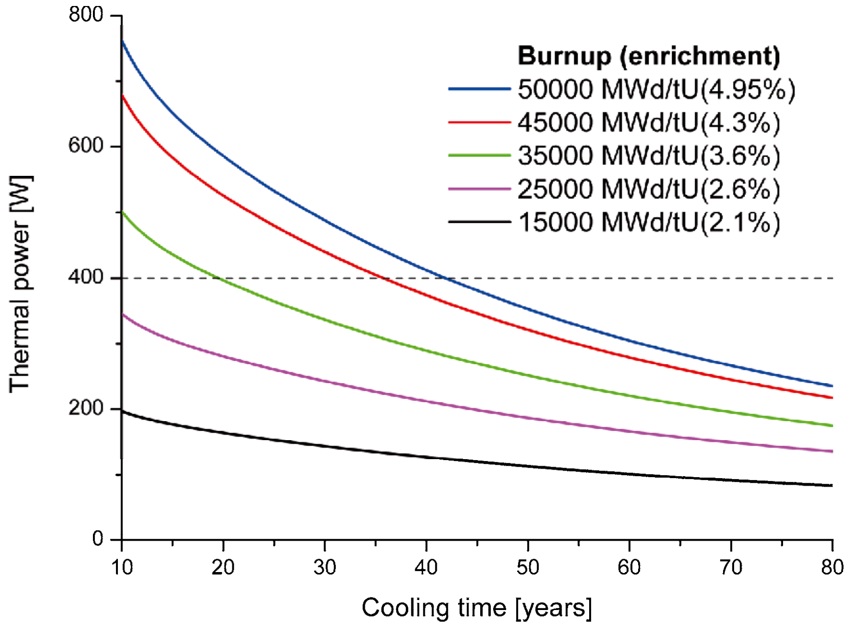


Figure 3: *Thermal power (decay heat) of a fuel assembly as a function of cooling time after irradiation in a PWR reactor for different burnups and initial enrichments. Dotted line indicates proposed average SFA decay heat for deep repository.*

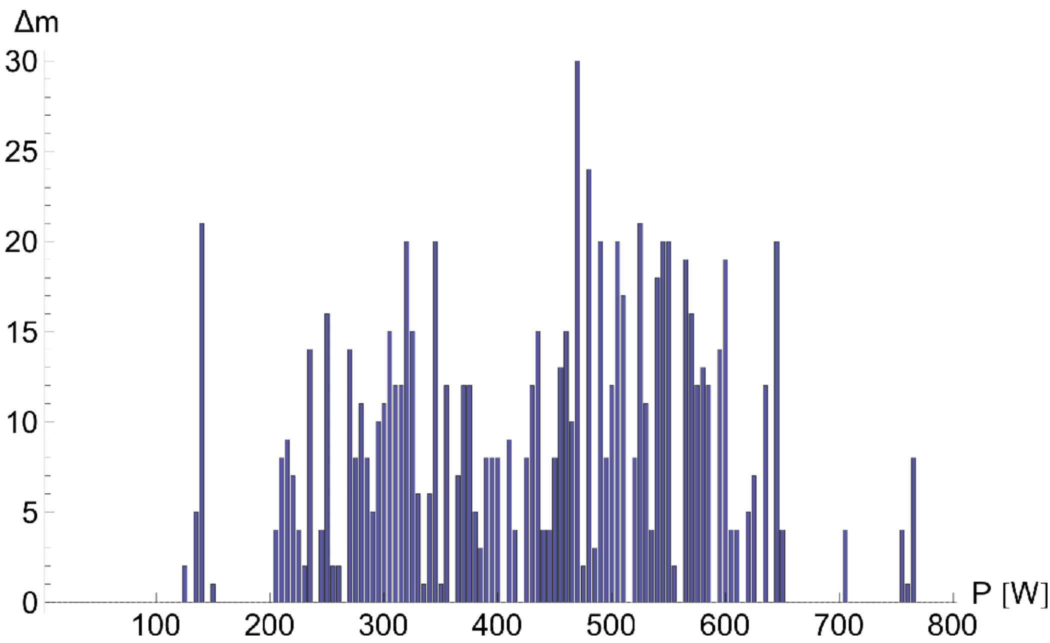


Figure 4: *Distribution of number of spent fuel assemblies over certain power intervals for NPP Krško spent fuel inventory (up to 2007) in 2020.*

Furthermore, we assume that thermal power (decay heat) as a function of time is known for all SFAs of interest. Actually, values adopted in this discussion were calculated using the ORIGEN 2.1 [5] code for SFA of NPP Krško. The SFA data needed for decay heat calculations were provided by the CORD-2 [6] software package. In 2007, there were exactly 874 SFAs in the spent fuel pit. The expected numbers for 2023 and 2043 are approximately 1760 and 2110, respectively.

3 OPTIMIZATION OF SPENT FUEL ARRANGEMENT

The canisters containing SFAs are to be arranged in a rectangular 2-D lattice with equidistant canister positions. Several studies of heat propagation in and around the repository have been performed [7-12] but most of them for an infinite number of canisters. If the lattice is large enough (at least ~1000 canisters), the additional heat sink along the edges can be neglected to form an equal condition for all canisters – power limit of P_{max}. It should be stressed that this is a conservative estimate since repository edges would allow for higher thermal power density. The limit P_{max} must not be exceeded under any circumstances. If such an arrangement of SFAs in canisters is not possible, we have to either wait for the spent fuel to cool down or leave some of the canisters partially empty. Naturally, we try to minimize the required number of canisters to reduce expenses. Additionally, we aim to reduce the required cooling time by optimizing the combination of the SFAs in canisters, considering abovementioned restrictions.

In this discussion, according to [12], we use the default value for power limit per canisters of P_{max} = 1600 W (see also Figure 3) and a maximum of 4 SFAs per canister. Even considering all the described simplifications, there is no hope of finding an optimal solution. In fact, we have proven [13] that the problem of combining SFAs in canisters according to decay heat (the so-called Canister Filling Problem) is an NP-hard problem, polynomially equivalent to the well-known Bin Packing Problem [14]. Our optimization method using constructive heuristics is described in [13,15]. The method has been successfully tested on both random and realistic input data [16].

4 RESULTS

When we have required data, i.e. thermal power (decay heat), for each SFA of certain SNF inventory at certain point in time, we can calculate the number of canisters at that point of time regarding the limits of 4 SFAs per canister and power limit P_{max}. In further discussion, the term “cooling time” refers to the actual cooling time of the SFA of the last NPP cycle. For three different NPP Krško SNF inventories, we calculated the required number of canisters as a function of cooling time after the last considered fuel cycle (Figures 5-7). The non-smooth behaviour of the solution is due to discreteness of the problem and time resolution (0.2 years).

The calculated number of canisters M is also compared to the theoretical lower bound $M_{\min}$:

$$M_{\min} = \max\{M_{\min,1}, M_{\min,2}\}, \quad M_{\min,1} = \left\lceil \frac{m}{4} \right\rceil, \quad M_{\min,2} = \left\lceil \frac{P_{tot}}{P_{\max}} \right\rceil, \qquad (1)$$

where m is the total number of SFAs, P_{tot} is the total SNF thermal power, and $\lceil x \rceil$ denotes the ceiling of x .

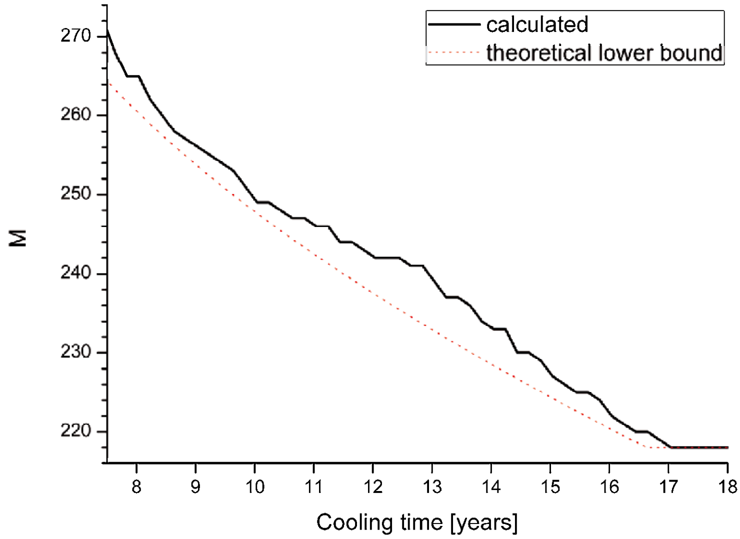


Figure 5: *Number of canisters as a function of cooling time for NPP Krško 2007 SNF inventory (a total of 22 fuel cycles).*

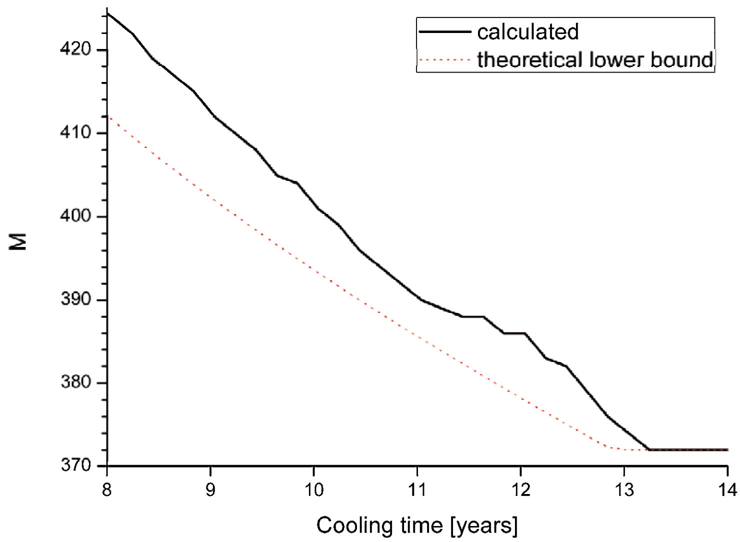


Figure 6: *Number of canisters as a function of cooling time for NPP Krško expected SNF inventory in case of NPP shutdown in 2023 (a total of 32 fuel cycles).*

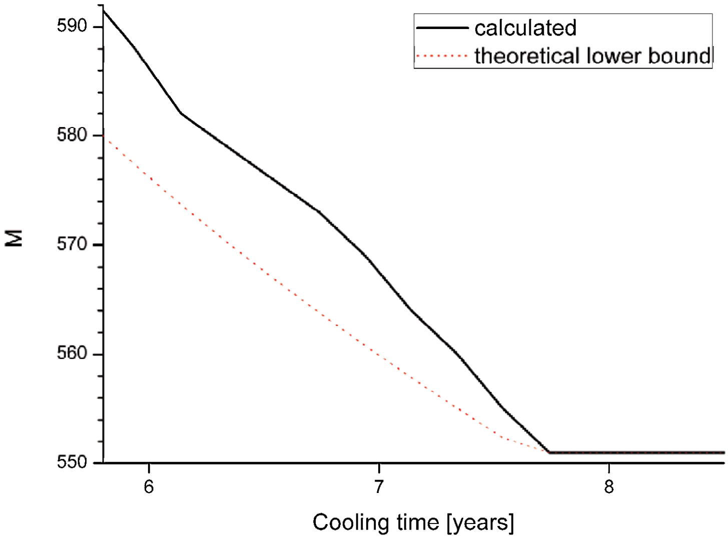


Figure 7: *Number of canisters as a function of cooling time for NPP Krško expected SNF inventory in case of NPP shutdown in 2043 (a total of 45 fuel cycles).*

Obviously, since the spent fuel decay heat decreases with time, the required number of canisters in the optimal solution cannot increase. Furthermore, the optimal solution for the number of canisters (which we do not know) lies anywhere between the calculated value and theoretical lower bound. Unfortunately, the lower bound is our only reference value; however, according to the fact that our optimization problem is not approximable within 3/2 [17] (there exists no algorithm that finds a solution within 3/2 of the optimal solution, for any input data and in computer time, polynomially dependent on the input data length) we find that our optimization method is successful.

The costs related to installation of additional canisters in final deep spent fuel repository are much higher compared to the interim storage costs. The obvious strategy is to wait until we are able to fill all the canisters in such a manner to reach the minimum number of canisters $\lceil m/4 \rceil$. The optimal deposition time is defined as the time interval between the end of the last NPP cycle and the moment when we are able to fully fill all the canisters with SFA not exceeding maximal allowed power per canister P_{max}.

Figure 8 presents a more general view on optimal deposition time. Clearly, when we raise the maximal allowed power P_{max} (for example because of change in repository location), we are able to deposit the fuel earlier, and vice versa. Also, the plant lifetime extension has a similar effect on optimal deposition time since the average SFA cooling time at the moment of NPP shutdown is longer and, consequentially, the average thermal power per assembly lower.

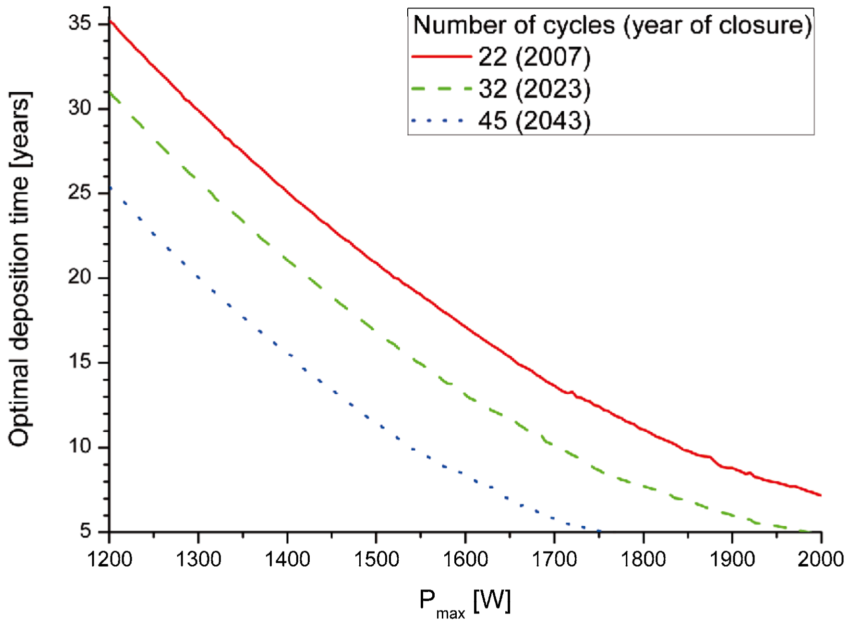


***Figure 8:** Optimal deposition time as a function of maximal allowed power per canister P_{max} for different plant operation scenarios.*

5 CONCLUSION

In spite of the possibility of fuel reprocessing, the option of direct spent nuclear fuel disposal is still attractive. The current strategy of the Slovenian Agency for Radwaste Management (ARAO), also chosen by Sweden, Finland, and South Korea, is terminal disposal in deep repository.

In this connection, we analyzed the interaction (heat exchange) between spent fuel and the host rock. We calculated spent fuel heat release for the Krško Nuclear Power Plant, and optimized the (hypothetical) arrangement of spent fuel assemblies in metal canisters in the repository. In this paper, following some simplifications, we assumed that the upper limit for allowed thermal power (decay heat) per canister was fixed. In future, this condition could be adjusted or generalized and coupled with calculations of heat propagation in and around the repository.

ACKNOWLEDGEMENT

This work was funded by the Slovenian Agency for Radwaste Management (ARAO) under project number ARAO 083-08.

References

[1] **N. Železnik, I. Mele, T. Jenko, V. Lokner, I. Levanat, A. Rapić**: *Program razgradnje NEK in odlaganja NSRAO in IJG (Program of NPP Krško Decommissioning and SF & LILW Disposal)*, ARAO-T-1123-03, ARAO (Agency for Radwaste Management), Ljubljana, Slovenia, and APO (Agency for Hazardous Waste), Zagreb, Croatia, 2004.

[2] **A. G. Milnes**: *Guide to the documentation of 25 years of geoscientific research (1976-2000)*, TR-02-18, VBB Anläggning AB, Swedish Nuclear Fuel and Waste Management Co, 2002.

[3] *Updated Safety Analysis Report for the Nuclear Power Plant Krško*, Revision 12.

[4] **M. Ravnik, G. Žerovnik, L. Snoj, M. Kromar:** *Izračun izotopske sestave in sproščene toplote iz izrabljenega jedrskega goriva iz NEK*, Jožef Stefan Institute, IJS-DP-9841, Rev. 2, 2008.

[5] *ORIGEN2, Isotope Generation and Depletion Code*, Oak Ridge National Laboratory, 1980.

[6] **A. Trkov, M. Ravnik:** *CORD-2 Package for PWR Core Design Calculations*, Proc. Int. Conf. on Reactor Physics and Reactor Computations, Beer-Sheva, Tel-Aviv, Israel, January 23-26, pp. 371-378, 1994.

[7] **L. Ageskog, P. Jansson:** *Heat propagation in and around the deep repository*, TR-99-02, VBB Anläggning AB, Swedish Nuclear Fuel and Waste Management Co, pp. 21-32, 1999.

[8] **J. Rutqvist, L. Börgesson, M. Chijimatsu, A. Kobayashi, L. Ling, T. S. Nguyen, J. Noorishad, C. F. Tsang:** *Thermohydromechanics of Partially Saturated Geological Media: Governing Equations and Formulation of Four Finite Element Models*, International Journal of Rock Mechanics & Mining Sciences 38, 105 (2001).

[9] **J. Rutqvist, L. Börgesson, M. Chijimatsu, T. S. Nguyen, L. Ling, J. Noorishad, C. F. Tsang**: *Coupled Thermo-hydro-mechanical Analysis of a Heater Test in Fractured Rock and Bentonite at Kamaishi Mine – Comparison of Field Results to Predictions of Four Finite Element Codes*, International Journal of Rock Mechanics & Mining Sciences, 38, 129 (2001).

[10] **M. Chijimatsu, T. S. Nguyen, L. Ling, J. De Jonge, M. Kohlmeier, A. Millard, A. Rejeb, J. Rutqvist, M. Souley, Y. Sugita:** *Numerical Study of the THM Effects on the Near-field Safety of a Hypothetical Nuclear Waste Repository-BMT1 of the DECOVALEX III. Part 1; Conceptualization and Characterization of the Problems and Summary of Results*, International Journal of Rock Mechanics & Mining Sciences, 42, 720 (2005).

[11] **A. Millard, A. Rejeb, M. Chijimatsu, L. Ling, J. De Jonge, M. Kohlmeier, T. S. Nguyen, J. Rutqvist, M. Souley, Y. Sugita:** *Numerical Study of the THM Effects on the Near-field Safety of a Hypothetical Nuclear Waste Repository-BMT1 of the DECOVALEX III. Part 2; Effects of THM Coupling in Continuous and Homogeneous Rocks*, International Journal of Rock Mechanics & Mining Sciences, 42, 731(2005).

[12] **J. Rutqvist, M. Chijimatsu, L. Ling, A. Millard, T.S. Nguyen, A. Rejeb, Y. Sugita, C. F. Tsang:** *Numerical Study of the THM Effects on the Near-field Safety of a Hypothetical Nuclear Waste Repository-BMT1 of the DECOVALEX III. Part 3; Effects of THM Coupling in Sparsely Fractured Rocks*, International Journal of Rock Mechanics & Mining Sciences, 42, 745 (2005).

[13] **G. Žerovnik, L. Snoj, M. Ravnik:** *Optimization of Spent PWR Fuel filling in Canisters for Deep Repository*, Nuclear Science & Engineering, 163, 183 (2009).

----

[14] **B. Korte, J. Vygen**, *Combinatorial Optimization, Theory and Algorithms*, Springer Verlag, pp. 407-422, 2000.

[15] **G. Žerovnik, M. Ravnik, L. Snoj, M. Kromar:** *Optimizacija polnitve vsebnikov z izrabljenim jedrskim gorivom iz NEK glede na največjo dovoljeno toplotno moč*, Jožef Stefan Institute, IJS-DP-10075, Rev. 0, 2009.

[16] **G. Žerovnik, J. Žerovnik:** *Experimental Comparison of Constructive Heuristics for the Canister Filling Problem*, Proc. Int. Symposium on Operational Research SOR'09, Nova Gorica, Slovenia, September 23-25, pp. 129-135, 2009.

[17] **M. R. Garey, D. S. Johnson:** *Computers and Intractability: A guide to the theory of NP-completeness*, W. H. Freeman and Company, San Francisco, 1979.

Nomenclature

(Symbols)	(Symbol meaning)
NPP	nuclear power plant
SNF	spent nuclear fuel
PWR	pressurized water reactor
SFA	spent fuel assembly
P	(thermal) power
Δm	number of SFA per interval of power
P_{max}	(thermal) power limit for canisters
M	number of canisters
M_{min}	theoretical lower bound for the number of canisters
P_{tot}	total (thermal) power of SNF inventory

Journal of Energy Technology

JET Volume 2 (2009), p.p. 61 - 68

Issue 4, November 2009

http://www.fe.uni-mb.si/si/e-jet/index.php

RENEWABLE ENERGY FOR NORTH-WEST CROATIA

OBNOVLJIVA ENERGIJA ZA SEVERNO-ZAHODNO HRVAŠKO

J. Domac[1], S. Djukic[2]

Keywords: Renewable energy, Rational energy use, north-west Croatia, regional energy agency

Abstract

North-west Croatia Regional Energy Agency has been founded in 2007 by Zagreb County, Karlovac County, Krapina-Zagorje County and City of Zagreb under the framework of the Intelligent Energy Europe programme. The main objective and role of the Agency are promoting and encouraging of regional sustainable development in the fields of energy and environmental protection through renewable energy sources (RES) utilization and energy efficiency measures implementation. The Agency provides information and advice to cities and municipalities and a number of other services based on specific local energy needs. This paper describes main activities and results of the Agency. Specific project activities are described in area of strategic documents and support, sustainable energy management in cities, renewable energy promotion, international cooperation and other activities. Carrying out all described and many already planned sustainable energy projects, the Agency will succesfully support its counties, cities and municipalities in making use of energy in this region sustainable and efficient.

Povzetek

Severozahodna Hrvaška Regionalna agencija za energijo je bila ustanovljena leta 2007. Ustanovile so jo občine Zagreb, Karlovec, Krapinsko-zagorska in občina Mesto-Zagreb v okviru programa Inteligentna energija za Evropo. Glavni cilj in vloga Agencije je pospeševanje in spodbujanje regionalnega trajnostnega razvoja na področju energije in varstva okolja, obnovljivih virov energije (OVE), uporaba in izvajanje ukrepov energetske učinkovitosti. Agencija

[1] Julije Domac, Ph.D.,

[2] Sanda Djukic, B.Sc. Tel: + 385 1 777 5494, Fax: +385 1 309 8316, E-mail address: sdjukic@regea.org

----

zagotavlja informacije in nasvete v mestih in občinah in številnih drugih storitev, ki temeljijo na specifični lokalni potrebi po energiji. Ta prispevek opisuje glavne dejavnosti in rezultate dela agencije. Posebne projektne dejavnosti so opisane na področju strateških dokumentov in podpore trajnostnemu upravljanju z energijo v mestih, spodbujanju obnovljivih virov energije, mednarodno sodelovanje in druge dejavnosti. Z izvajanje vseh opisanih in načrtovanih projektov za trajnostni razvoj in energetsko učinkovitost, bo agencija nudila uspešno podporo svojim občinam in mestom pri uporabi energije v teh regijah.

1 INTRODUCTION

North-western Croatia is an area of abundant natural resources and high potential for renewable energy sources utilization. Specifically, there are vast natural forest resources of app. 300.00 ha, which (coupled with the large number of wood processing companies and the long tradition of fuel wood use in households) ensure a fertile ground for biomass project development. Apart from biomass, considerable geothermal resources are present in the area, which are currently being utilized only for space heating in some spa and recreation facilities. In Karlovac County, there is an abundance of small river flows and utilization of small hydro power plants has a long tradition. Currently, there are several small hydro power plants in the category of several MW of installed capacity and several opportunities exist for the instalment of new plants. The Zagreb area has very high potential for the implementation of measures to increase energy efficiency (RUE), considering its high population density, large number of public and residential buildings and industrial facilities.

The North-west Croatia Regional Energy Agency was founded in 2007 by Zagreb County, Karlovac County, Krapina-Zagorje County and the City of Zagreb under the framework of the Intelligent Energy Europe programme as a separate and independent non-profit legal entity. In total, Croatia consists of 21 counties including the city of Zagreb, which also has the status of a county. The region of north-west Croatia includes three counties – Zagreb County, Karlovac County, Krapina-Zagorje County – and the City of Zagreb (the capital of Croatia). The total area covered is approximately 8.500 km^2 and include 20 smaller towns and 68 small municipalities with a population of about 1.3 million people.

The main objective and role of the agency are promoting and encouraging regional sustainable development in the fields of energy and environmental protection through renewable energy source (RES) utilization and energy efficiency measures implementation. The agency provides information and advice to cities and municipalities and a number of other services based on specific local needs for energy.

The vision of the agency are counties and towns in north-western Croatia managing energy in the best possible way, and entire region as an example of the successful use of renewable energy sources and energy efficiency principles implementation, among other successful European regions. Services that agency provide include:

- Information, consultation and education on energy use,
- Support for development and implementation of local and regional energy plans,
- Energy audits and systematic energy management in public buildings,
- Raising public awareness about energy efficiency and renewable energy use,
- Ensuring domestic and foreign sources of funding for projects and activities.

The North-west Croatia Regional Energy Agency is the first such agency in Croatia, meaning that it is a forerunner in RES and RUE project implementation. The agency cooperates with many national, regional and local agencies and number of established energy management energies across Europe.

2 MAIN PROJECTS AND ACTIVITIES

In cooperation with its founders – three counties and the city of Zagreb as well as cities and municipalities in the region – Agency has launched many projects in order to significantly improve energy management and implement established goals. Projects are implemented in cooperation with the private and public sectors, local municipalities, EU and partners from European countries and other international organisations (International Energy Agency, UN Food and Agricultural Organization, UN Organization for Industrial Development and others).

2.1 Strategic documents and support

One of the agency's priorities for 2009 is the creation of strategic documents for its founders, i.e. for all three counties and the city of Zagreb. Strategies of sustainable energy use for Krapina-Zagorje, Zagreb and Karlovac County have already been finalized; during the second half of 2009, the Strategy of Sustainable Energy Use and a Sustainable Energy Action Plan (SEAP) for the City of Zagreb will be completed. Those are key documents that include an overview of existing energy infrastructure and past experience, analyze potentials and opportunities, anticipate possible effects and obstacles, but also contain very specific recommendations for actions and measures in order to improve energy efficiency on local levels.

The strategies are a joint product of all county stakeholders and hence the first step was their identification and grouping. Direct inclusion of stakeholders within the development process was ensured through organising consultations and receiving feedback from public presentations of the strategy draft. The current status of energy infrastructure within the county and experiences in the utilisation of various renewable energy sources and energy efficiency measures served as the starting point for the definition of future developments. Efforts have been made to harmonise this strategy with the relevant national and EU legislation and strategic documents, which have been reviewed and presented. The overview of the current economic and employment status of the county, as well as the possible contribution from renewable energy source utilisation and energy efficiency towards economic development is an integral part of the Strategy. The two final chapters represent the most important parts and include the evaluation of the energy potential, measures and recommendations for the utilisation of various renewable energy sources and increased energy efficiency within the county, the definition of specific targets and the proposal of organisational measures and action plan for the period from 2009 to 2011.

The proposed measures and activities within the action plan have been defined in such a way that their implementation results in achieving the defined targets. They were grouped in four basic categories:

- strategic and implementing documents, planning;
- capacity building;
- demonstration activities, implementation and promotion;
- financial and supporting mechanisms.

In order to clearly define the responsibilities for the implementation of various measures and activities, each category was further divided based on the identified stakeholders within the counties. Additionally, for each activity, the implementation dynamics and success criteria have been defined.

2.2 Sustainable energy management in cities

An important agency priority is encouraging cities through Covenant of Mayors initiative to create their own Sustainable Energy Action Plans. In this context, the agency has already provided expert support for the City of Zagreb and the City of Ivanić-Grad, which joined this initiative in early 2009.

The same is expected from cities of Karlovac, Velika Gorica and Klanjec before the end of 2009; the Agency will continue its efforts to encourage other cities in the region to follow.

In this area, particularly important is the agency activity in introduction and active implementation of systematic energy management for public buildings in cities. This, now *standard package* include the establishment of an energy consumption database for public buildings, implementation of energy audits, identification of critical energy consumption points, monitoring during and after reconstruction and improvement, the education building officers and participation in the well-known EU Display campaign. The first city to start this activity was Zapresic while the cities of Karlovac and Velika Gorica will start very soon.

It has to be noted that the agency signed an agreement with Energie-Cités, an organization engaged in promoting sustainable energy use in European cities, and has obtained right for implementation EU Display campaign in the entire area of north-western Croatia. Display posters have so far been placed on 12 schools in Krapina-Zagorje County, 10 public buildings in City of Zapresic, and will be soon implemented in the cities of Zagreb, Karlovac and Velika Gorica.

2.3 Renewable energy promotion

However, two projects deserve special attention when analysing the activities and results of the agency so far. The promotion (and much more than just promotion) of solar collectors in private households and the implementation of small-scale biomass district heating systems at the municipal level are the most recognised and successful programmes of the new agency.

The project *I can have solar collectors, too!* aims to promote use of solar energy and raise awareness of renewable energies environmental and financial benefits. The project will support the installation of solar panels in 120 selected houses (in 2009, in three counties) through means of co-financing, and perform a number of accompanying awareness raising activities. In the first phase of the project, an open public contest is to be run for the households that will be selected for solar systems for heating and water heating installation. In the households selected according to defined criteria (roof isolation, walls isolation, windows condition...), solar systems will be installed in the second phase of the project and co-financed in the amount of 40% or up to the maximum of 1 600 EUR per household. Total annual energy savings in 60 households of Karlovac County covered by this project are expected to be 82,800 kWh. The project was launched by the North-west Croatia Energy Agency, which is also the executive body of the implementation. Project funding was ensured from counties and the national Energy Efficiency and Environment Protection Fund.

***Figure 1**: Project leaflet*

Although biomass (in the form of fuel wood) is still widely used in Croatia, there are still no district biomass heating systems as in many other central European countries. The agency identified and – together with municipality leaders – developed five promising biomass district heating projects. They are all of a similar scale of about 1 MW thermal and located around NW Croatia (municipalities of Krasic, Pokupsko, Rakovica, Slunj and Zakanje). At the moment, larger buildings are heated with light fuel oil, while in residential buildings either light fuel oil or wood are used for heating. The first plants are expected in operation during 2010.

2.4 International cooperation

Agency efforts are also focused on transfer of knowledge, experience and technology from the European Union to the region. In this context, the agency has implemented the following international projects:

- FP6 Concerto SERVE project – Sustainable Energy for Rural Village Environments

  This project aims to develop a sustainable region in North Tipperary through the implementation of actions in the field of sustainable energy. Actions will include energy upgrades for existing dwellings, installation of renewable energy heating systems, development of an eco-village in Cloghjordan and the development of a district heating system. Within the project, the Agency is leading Work Package 6: Socio-economic Analysis and Research.

- IEA Bioenergy Task 29 – Socio-economic Drivers in Implementing Bioenergy Projects

  The IEA Bioenergy Task 29 is an ongoing initiative from 1 January 2000 with the aim of investigating different regional and national achievements in the recognition and evaluation of social and economic benefits of biomass utilisation and drivers in implementing bioenergy projects. Among others, deliverables include position papers outlining the benefits of bioenergy, brochures, scientific papers and presentations, posters and an educational website. The participating countries in the 2010-2012 period are Canada, Croatia, Germany Japan, Norway and United Kingdom.

- IEE – SMART- Strategies to Promote Small-Scale Hydro-Electrical Production in Europe

----

The project has been co-financed by the European Commission through the 2006 Intelligent Energy Europe Programme (IEE) and the main objective is to give clear contributions to eradicate non-technological barriers, and provide helpful tools for European, national, regional and local authority decision-makers for increasing the implementation of small-scale hydro electricity plants on their own territory.

- Interreg/Phare/Cards – Systematic Energy Management (Karlovac County).

  The goal of the project is to improve the efficiency of energy use and to reduce energy consumption in the public institutions of Karlovac County, implementing a model of systematic management of energy using regular reports on energy consumption. Tasks of the agency are the collection and analysis of data on energy consumption in buildings on a monthly basis using a sophisticated computer program, implementation of a detailed energy review of 20 public buildings owned by Karlovac County and the development of investment studies for 20 public buildings owned by Karlovac County.

It should be noted that the agency has become a member of FEDARENE (the Association of regional and local energy agencies), the National Reference Centre of the European GREENLIGHT program and has participated in a workshop for preparation of SEAP in the Covenant of Mayors organized by the European Commission JRC as the only Croatian participant.

2.5 Other activities

Education and promotion are the agency's permanent and constant activities. It continuously prepares and publishes different brochures about energy consumption. A brochure on sustainable building and efficient street lighting published in 2008; in 2009 a brochure on solar collectors and small biomass furnace will be prepared. One of the most important deliverables is certainly a picture book *Tell Me a Story about Renewable Energy Sources*, which has been published in 5,000 copies so far. The agency has developed an educational program for high school students, which includes lectures, educational materials, field trips and a competition. Program was implemented in more than 20 selected high schools in the region.

Figure 2: *Illustration from a picture book Tell Me a Story about Renewable Energy Sources*

The agency was a co-organizer with City of Zagreb UNDP (Zagreb office) of the conference *Sustainable Development of Cities*. The conference was intended for mayors, representatives of local governments, universities, scientific institutions, engineers, architects, investors in the construction sector, development and energy agencies and media. The main objective was the promotion of energy management in the Croatian cities with an emphasis on the environment, sustainable energy management of public utility systems, as well as the exchange of knowledge and experiences between many European and Croatian cities. In total, more than 500 people attended the conference which was opened by the president of Croatia, Stjepan Mesic.

One very important activity for the agency is project support for cities and municipalities. Among the numerous activities and projects in many cities and municipalities in the area, it is important to emphasize two projects: modernization of public lighting in the city of Ogulin, and modernization of lightning for the Zelenjak monument in the municipality of Kumrovec as well as more than 20 other public lighting projects in cities and municipalities.

3 FUTURE ACTIVITIES AND THE WAY FORWARD

Following direct results and outcomes of the agency's activities, the following developments are already or will be very soon achieved:

1. Formulated regional energy strategy with a clear roadmap for greater utilization of renewable energy sources and improvement of energy efficiency with a detailed action plan for each of the four counties of north-west Croatia,
2. Identification and start-up of demonstration activities:
   - Selection of local schools and other public buildings as demonstration projects for energy efficiency measures implementation,
   - Installation of large number of solar systems in households within the region,
   - Installation of biomass heating boilers in households within the region,
   - Identification and start-up of demonstration projects, resulting in installation of biomass district heating systems in smaller towns and villages within the region,
   - Identification and start-up of demonstration projects of heat pumps utilization for public and private buildings in the region,
   - Utilization of small-hydro potential on rivers and flows in the region,
   - Start-up project for utilization of biofuel and natural gas for city public transport in cities within the region,
3. Establishment of a permanent advisory service for local municipalities/regional authorities in order to enable their increased participation and involvement in future renewable energy and energy efficiency projects in the region.
4. Implemented a comprehensive campaign for public education and promotion (comprehensive public opinion survey, publication and distribution of education and promotion materials, organization of energy training workshop for specific target groups),
5. Increased EU cooperation in related areas (other EU energy agencies, etc.).

A significant portion of the aforementioned projects has already been implemented. These actions and projects will have a long term impact on development of joint cooperation, markets and links in field of renewable energy, energy efficiency and beyond, public awareness raising, public participation and capacity building, identification of flagship opportunities for joint actions, delivering projects and actions on the ground, reducing pollution from energy production (including GHG emissions), groundwater protection, the creation of a positive economic environment, generation of jobs and income opportunities.

4 CONCLUSIONS

This positive development will, in the long-term, contribute a strategic goal of the regional authorities in north-western Croatia and support current community policy initiatives. The analysed activities and trained people combined with all ongoing actions from other stakeholders should the enable accomplishment of the goals set out in the National Energy Strategy and successfully follow European energy policy.

Carrying out those and many other potential renewable energy projects, the *North-west Croatia Energy Agency* will stand alongside cities and municipalities and provide them expert assistance and support. The renewable energy potentials in this part of Croatia certainly will not remain unused.

Nomenclature

RUE	Renewable energy sources
RUE	Rational use of energy
SEM	Systematic Energy Management
UNDP	United Nations Development Programme
FEDARENE	European Federation of Regional Energy and Environment Agencies
GHG	Greenhouse gas
SEAP	Sustainable Energy Action Plan
JRC	Joint Research Centre

Journal of Energy Technology

http://www.fe.uni-mb.si/si/e-jet/index.php

AUTHOR INSTRUCTIONS (MAIN TITLE)

SLOVENIAN TITLE

Authors, Corresponding author[ℜ]

Key words: (Up to 10 keywords)

Abstract

Abstract should be up to 500 words long, with no pictures, photos, equations, tables, only text.

Povzetek

(In Slovenian language)

Submission of Manuscripts: All manuscripts must be submitted in English by e-mail to the editorial office at jet@uni-mb.si to ensure fast processing. Instructions for authors are also available online at http://www.fe.uni-mb.si/si/e-jet/index.php.

Preparation of manuscripts: Manuscripts must be typed in English in prescribed journal form (Word editor). A Word template is available at the Journal Home page.

A title page consists of the main title in the English and Slovenian languages; the author(s) name(s) as well as the address, affiliation, E-mail address, telephone and fax numbers of author(s). Corresponding author must be indicated.

Main title: should be centred and written with capital letters (ARIAL **bold** 18 pt), in first paragraph in English language, in second paragraph in Slovenian language.

Key words: A list of 3 up to 6 key words is essential for indexing purposes. (CALIBRI 10pt)

Abstract: Abstract should be up to 500 words long, with no pictures, photos, equations, tables, - text only.

Povzetek: - Abstract in Slovenian language.

[ℜ] Corresponding author and other authors: Title, Name and Surname, Tel.: +XXX x xxx xxx, Fax: +XXX x xxx xxx, Mailing address: xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx, E-mail address: email@xxx.xx

----

Main text should be structured logically in chapters, sections and sub-sections. Type of letters is Calibri, 10pt, full justified.

Units and abbreviations: Required are SI units. Abbreviations must be given in text when firstl mentioned.

Proofreading: The proof will be send by e-mail to the corresponding author, who is required to make their proof corrections on a print-out of the article in pdf format. The corresponding author is responsible to introduce corrections of data in the paper. The Editors are not responsible for damage or loss of manuscripts submitted. Contributors are advised to keep copies of their manuscript, illustrations and all other materials.

The statements, opinions and data contained in this publication are solely those of the individual authors and not of the publisher and the Editors. Neither the publisher nor the Editors can accept any legal responsibility for errors that could appear during the process.

Copyright: Submissions of a publication article implies transfer of the copyright from the author(s) to the publisher upon acceptance of the paper. Accepted papers become the permanent property of "Journal of Energy Technology". All articles published in this journal are protected by copyright, which covers the exclusive rights to reproduce and distribute the article as well as all translation rights. No material can be published without written permission of the publisher.

Chapter examples:

1 MAIN CHAPTER

(Arial bold, 12pt, after paragraph 6pt space)

1.1 Section

(Arial bold, 11pt, after paragraph 6pt space)

1.1.1 Sub-section

(Arial bold, 10pt, after paragraph 6pt space)

Example of Equation (lined 2 cm from left margin, equation number in normal brackets (section.equation number), lined right margin, paragraph space 6pt before in after line):

$$c = \sqrt{a^2 + b^2} \qquad (1.1)$$

Tables should have a legend that includes the title of the table at the top of the table. Each table should be cited in the text.

Table legend example:

Table 1: *Name of the table (centred, on top of the table)*

Figures and images should be labelled sequentially numbered (Arabic numbers) and cited in the text – Fig.1 or Figure 1. The legend should be below the image, picture, photo or drawing.

Figure legend example:

Figure 1: *Name of the figure (centred, on bottom of image, photo, or drawing)*

References

[1] **Name. Surname:** *Title,* Publisher, p.p., Year of Publication

Example of reference-1 citation: In text, Predin, [1], text continue. **(Reference number order!)**

JET

JET Journal of ENERGY TECHNOLOGY Vol. 2/4 2009 UNIVERSITY OF MARIBOR, FACULTY OF ENERGY TECHNOLOGY

GEN ENERGIJA

skupina group FOM
With perfect respect for diversity!

ISSN 1855-5748