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Andrej PREDIN

Slovenija na poti v nizko-ogljično družbo?

Trajnostni razvoj energetike v Sloveniji mora biti oblika razvoja, ki zadošča potrebam po energiji, ne da bi pri tem ogrožal okolje in s tem možnosti življenja in razvoj prihodnjim generacijam, da prav tako zadostijo svojim potrebam. V tej smeri (vsaj upam tako) je bil spisan tudi dokument Republike Slovenije, sveta vlade RS za konkurenčnost, Strateški dokument sektorske razvojne skupine ENERGETIKA IN TRAJNOSTNI VIRI ENERGIJE, z dne 10 novembra, 2008. V odseku, kjer navaja premog je zapisano, da premog danes predstavlja pomemben primarni vir za proizvodnjo električne energije (v strukturi proizvodnje približno tretjino proizvodnje električne energije v RS). Predvideno je, da se bo v prihodnosti proizvodnja električne energije iz premoga do leta 2030 celo podvojila!? V duhu zapisanega strateškega dokumenta me bega odločitev vlade RS, ki se je odločila za izgradnjo novega bloka TEŠ 6, z zastarelo tehnologijo sežiganja premogovega prahu pri povišanem tlaku (CCT). Ta tehnologija se je pojavila v 90. letih prejšnjega stoletja. (kombinirani plinsko parni proces PCC in FBC tehnologiji). Če bolje razmislimo in ob poznavanju trendov razvoja, bi se morala vlada odločiti vsaj za IGCC (Integrated Gasification Combined Cycle) tehnologijo, ki bi omogočala Velenjski-Šoštanjski regiji nadaljnji razvoj na področju energetike, tudi ko bodo izčrpane zaloge premoga v Velenju. Gre za kombiniran plinsko parni proces s predhodnim uplinjanjem premoga. Prednost te tehnologije je v možnosti uporabe alternativnih goriv, kot so: lesna biomasa, odpadna olja, naftni odpadki, komunalni odpadki. Ob tem je zanimiva možnost uporabe zemeljskega plina ob priključitvi Slovenije na »Južni tok« ruskega plinovoda. V tem primeru je »tehnološki del« elektrarne sestavljen iz turbin, ki lahko koristijo različne vrste plinastih goriv. Ta novozgrajen blok bi v tem primeru deloval v strukturi trajnostnega energetskega razvoja Slovenije. Strukturno bi lahko bil vključen vse do takrat, ko bodo tehnologija uporabe obnovljivih virov energije (OVE) tako razvita, da bomo v Sloveniji lahko pokrili vse energetske potrebe.

Is Slovenia on the way to low-level carbon society?

Sustainable energy development in Slovenia should perform as a development to fulfil today's energy needs without compromising the environment and, above all, giving future generations the possibilities of quality life and development of their own needs. In this direction (at least I hope so) was written the Strategy Plan of Development of Energy and Sustainable Energy Sources by the Council on Competitiveness of the Republic of Slovenia (dated 10 November, 2008). In the coal section, it is stated that today coal is an important primary source for electricity production (representing one third of electricity production in Sloveia). It is envisaged that in the future, by 2030, electricity production from coal will have doubled. In the spirit of the above strategy document, I am very surprised by the Government's decision for the implementation of a new TES 6 block, with outdated technology burning pulverised coal at an elevated pressure. This technology is from the 1990s (combined gas-steam process PCC and FBC technology). A better consideration on the part of the government, with the knowledge of today's development trends, would be the IGCC (Integrated Gasification Combined Cycle) technology, allowing the Velenje-Šoštanj region further development in the energy field, after the coal reserves in Velenje are exhausted. IGCC is a combined gas-steam process with previous coal gasification. The advantage of this technology is in its possibility of using alternative fuels such as wood biomass, waste oil, and municipal waste. It also has the opportunity of using natural gas when Slovenia is connected to the South Stream pipeline from Russia. In this case, the technology of the power plant consists of gas turbines, which can benefit from different types of gaseous fuels. This newly built block could be integrated into the structure of sustainable energy development, providing much needed energy until the technology of alternative energy sources will be fully developed to meet all energy needs in Slovenia.

Krško, August 2009

Andrej PREDIN

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NUCLEAR RENAISSANCE AS A VIABLE SOLUTION FOR REDUCING GREENHOUSE GASES – THE ENVIRONMENTAL IMPACT OF DIFFERENT ENERGY TECHNOLOGIES

JEDRSKA ENERGIJA ZMANJŠUJE EMISIJE TOPLOGREDNIH PLINOV - VPLIVI RAZLIČNIH TEHNOLOGIJ ZA PROIZVODNJO ELEKTRIČNE ENERGIJE NA OKOLJE

Tomaž Žagar[ℜ,1], Robert Bergant[2], Samo Fürst[3]

Keywords: emissions, environment, technology, electricity production

Abstract

Climate change is happening and represents one of the greatest environmental, social and economic threats facing the planet. The Intergovernmental Panel on Climate Change (IPCC), an association of scientists from all over the world, came to the conclusion that the main reason is the enhanced greenhouse effect.

[ℜ] Tomaž Žagar, PhD., GEN energija, d.o.o., Tel.: +386 (7) 491 0132, Fax: +386 (7) 490 1118, E-mail address: tomaz.zagar@gen-energija.si

[1] Tomaž Žagar, PhD., University of Maribor, Faculty of Energy Technology, Tel.: +386 (7) 620 2210

[2] Robert Bergant, PhD., GEN energija, d.o.o., Tel.: +386 (7) 491 0404, Fax: +386 (7) 490 1118, E-mail address: robert.bergant@gen-energija.si

[3] Samo Fürst, GEN energija, d.o.o., Tel.: +386 (7) 491 0136, Fax: +386 (7) 490 1118, E-mail address: samo.furst@gen-energija.si

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The production of electricity is, beside transportation, the most harmful contributor to the enhanced greenhouse effect. Unfortunately, the majority of electricity production is still based on a combustion of fossil fuels, e.g. coal, oil and gas. Renewable sources such as hydro, solar or wind are becoming increasingly preferable. Nuclear energy is also an important low-carbon energy source with insignificant impact on the environment. Its whole cycle emissions are at least as low as the emissions of above-mentioned renewable sources. Besides its environmental benefits, nuclear energy has also economical, spatial and social advantages over some other renewable sources.

The purpose of the article is to present integrated environmental impacts for different technology chains used for electricity production. Two separate and independent studies are shown in this intention. A summary of different studies, made by Organization for Economic Cooperation and Development (OECD), presents the comparison of environmental impacts of different technology chains for the electricity production sector, based on data supplied by the OECD organization's members. The study of the company GEN energija is focused on the comparison of environmental impacts of different technology chains that are feasible for electricity production in Slovenia, i.e. technologies such as nuclear, coal, gas, different renewable sources and a mixture of renewable sources, which include the hydro, biomass, wind and photovoltaic production.

The evaluation of the environmental impacts for different energy technologies is implemented within radius 10 km of the existing location of Nuklearna elektrarna Krško (NEK) site, in order to evaluate and present the environmental consequences of different electrical power producing energy technologies. Electrical power production from four potential nuclear reactor designs, imported coal-fired power generation, combined-cycle gas-fired generation, and renewable power generation sources, including hydroelectric generation, solar photovoltaic generation, wind generation, biomass cogeneration, and geothermal electric generation are considered.

Two assumptions for electrical power producing technologies are an installed capacity of 1,100 MWe and a 90% Baseload Capacity Factor. The renewable sources are evaluated as a resource mix (RES Mix) and are not capable reaching the required 90% Baseload Capacity Factor. It is assumed to have a combined 34% Baseload Capacity Factor if the evaluation region is expanded to the whole of Slovenia. For the RES Mix, 32% hydroelectric generation, 36% wind generation, 32% biomass cogeneration, <1% solar photovoltaic generation and <1% geothermal electric generation is assumed.

The evaluation of environmental impacts shows that nuclear has several advantages. It is superior in comparison to combined-cycle gas-fired generation and imported coal-fired power generation. Nuclear is also at least comparable with the RES Mix, if the RES Mix Baseload Capacity Factor is ignored; otherwise, it is superior.

Povzetek

Klimatske spremembe so vedno bolj intenzivne in predstavljajo vedno večje tveganje v našem življenju. Mednarodna skupina ZN-a o podnebnih spremembah, ki združuje znanstvenike s celega sveta, je potrdila, da je vzrok klimatskih sprememb antropogeno povečevanje izpustov toplogrednih plinov.

Eden izmed največjih povzročiteljev toplogrednih plinov, poleg transporta, je sektor proizvodnje energije. Razlog tiči v tem, da velik del proizvodnje elektrike še vedno temelji na izrabi fosilnih

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goriv, ki imajo največji doprinos k emisijam toplogrednih plinov. Zaradi potreb po zniževanju specifičnih emisij na pomembnosti zopet pridobiva tudi jedrska energija, ki sodi v nizko-ogljično proizvodnjo energije. Prav tako so njeni skupni vplivi na okolje in družbo ugodnejši ali vsaj tako ugodni kot vplivi obnovljivih virov.

Namen prispevka je prikaz celostnih vplivov na okolje pri proizvodnji električne energije pri uporabi različnih tehnologij. V ta namen sta prikazani dve ločeni in neodvisni študiji, in sicer povzetek različnih študij mednarodne organizacije za gospodarsko sodelovanje in razvoj (OECD) in študija podjetja GEN energija. Povzetek študij organizacije OECD obravnava primerjavo vplivov na okolje različnih tehnoloških verig za pridobivanje električne energije na osnovi podatkov, ki jih organizaciji OECD posredujejo njene članice. Študija GEN energije pa je osredotočena na primerjavo vplivov na okolje obravnavanih tehnologij, ki so smiselne ter izvedljive za proizvodnjo električne energije v slovenskem prostoru in sicer jedrske, premogovne, plinske, obnovljivih virov in mešanice obnovljivih virov, med katere spada vodna, biomasna, vetrna in fotovoltaična proizvodnja.

Ožje območje prikazanih vplivov obsega 10km radij okoli obstoječe lokacije Nuklearne elektrarne Krško. Cilj študije je ocenitev katera izmed tehnologij predstavlja najnižjo celostno obremenitev okolja pri pasovni proizvodnji proizvodni električne energije na lokaciji ob obstoječi Nuklearni elektrarni Krško. Zahtevi za novo proizvodno enoto sta instalirana električna moč 1100MWe in faktor razpoložljivosti enote 90%. Ocenjeno je, da mešanica obnovljivih virov ne more zadostiti osnovni zahtevi faktorja razpoložljivosti 90% pri instalirani električni moči 1100MWe. Doseže le vrednost 34%, ob razširitvi predvidenega območja na celotno Slovenijo. Delež posamezne tehnologije v mešanici obnovljivih virov predstavlja 32% vodna, 36% vetrna, 32% biomasna, <1 % fotovoltaična in <1% geotermalna proizvodnja električne energije. Druge obravnavane tehnologije zadostijo osnovnima faktorjema za novo proizvodno enoto. Zaključek ocenitve celostnih vplivov jasno pokaže, da ima jedrska tehnologija nesporno prednost v primerjavi s plinsko in premogovno tehnologijo. Tudi v primerjavi z obstoječo mešanico obnovljivih virov, ob neupoštevanju njenega faktorja razpoložljivosti, ima jedrska tehnologija nesporno prednost pri celostnem vplivu na okolje.

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1 INTRODUCTION

Climate change is a result of increasing greenhouse gas emissions and growing problem that requires interdisciplinary cooperation across the world. The Kyoto Protocol Alliance signatories have the objective of a 20% greenhouse emissions reduction in 2020, compared to 1986 levels. The instruments for achieving this are different across countries, but in general all signatories have to become low-carbon societies in all areas. An especially sensitive and important area in the transition to a low-carbon society is the sector of energy production, which has a large contribution to greenhouse gas emissions. Therefore, it is important for each country to have a detailed plan for the further development of this sector; this also has an important impact on the economic performance of the country. It is important to pursue development towards low-carbon, economically justified and sustainable technologies.

2 ELECTRICITY PRODUCTION IN SLOVENIA

The energy production sector combines heat production and electricity production. In recent years, Slovenia's electricity production has been insufficient, since annual average electricity import has reached over 20%. Such high input levels have been reducing the competitiveness of the domestic economy; therefore, new investments in the modernization of the electricity production as well as expansion of current capacity are necessary. Among the most important technologies for Slovenian electricity production are nuclear, coal, gas, hydro and renewable energy sources technologies.

In accordance with the legal commitments regarding the reduction of greenhouse gas emissions set by the EU 20-20-20 objectives, which call for 20% fewer GHG emissions, 20% lower final energy consumption and a 20% share of renewables in final energy consumption by 2020, production economy resources aims, greater economic competitiveness and sustainable development objectives, and all production technologies should be compared under the same principle before the decision for a particular technology in the process of extending the electricity production capacity should be made. The comparison should be based on the same basic platform as well as on the evaluation of individual technologies.

Slovenia has a similar procedure, as the one mentioned above, in the process of spatial planning called a strategic/comprehensive environmental impact assessment and an environmental impact assessment. These two processes are not a comparison with other technologies and the choice of the optimal solution, but only evaluation of the environmental acceptability of the individual plans without intervention on site. The Republic of Slovenia therefore has no legislation for the comparison of technologies that would serve for optimal decisions in the process of production capacity expansion.

Similar comparison studies are more common abroad. One such stuy was completed by the Organization for Economic Co-operation and Development (OECD), which has largest database for the comparison of technologies based on energy production factors. The analyses performed by the OECD were based on current actual data, delivered by countries all around the world. Therefore, we want to present the most important results of some OECD analysis as well as our study of environmental impacts of different energy technology options, enhanced with analysis and data, based on global scale expertise.

GEN energija is an energy company that wants to play an active role in the new cycle of investment in new electricity production capacity in Slovenia. To enhance GEN's technology decision with substantiated facts, the study of environmental impacts of different energy technology options for electricity production in Slovenia [1] was ordered from an internationally recognized engineering firm, the Washington Group International (a division of URS Corporation), which has a strong team of environmental experts.

3 RESULTS OF OECD's TECHNOLOGY COMPARISONS STUDIES

The Organization for Economic Co-operation and Development (OECD) made the comparison analyses of different technology chains [2]. These studies were based on information supplied by the organization's individual member states, as well as by countries that are not OECD members. The studies included the environmental, social and economic aspects of the entire energy chain from the begging to the end (life cycle assessment - LCA).

Science-based, industrial, international life cycle assessment (LCA) and life cycle management (LCM) data from all over the world can be found on http://www.ecoinvent.org/. The ecoinvent Centre is the world's leading supplier of consistent and transparent life cycle inventory (LCI) data of known quality. The results presented below are based on reports of Dones et al. [4 - 6]. Environmental (greenhouse gas emissions, SOX, NOX, non-radioactive waste, land use and accident risks), social (human health impacts) and economic indicators (use of energy and non-energetic resources) are presented.

3.1 Greenhouse gas emissions

Greenhouse gas emissions have a global impact on the environment, with a major role in global warming and climate change. Figure 1 shows a comparison of greenhouse gas emissions for each electricity production technology chain.

For each technology, the average data value is presented together net maximum and minimum values. The max and min values are also labeled with country codes, indicating the origin of the data.

Emissions are expressed in kgCO_2 equivalent per unit of generated energy. Lignite has the highest emissions in the UCTE (The Union for the Co-ordination of Transmission of Electricity) average, slightly above 1.2 kgCO_2-eq./kWh; coal has a slightly lower level, with the UCTE average of around 1.07 kgCO_2-eq./kWh. The chain of natural gas has the lowest level of emissions of fossil systems with UCTE average slightly above 0.6 kgCO_2-eq./kWh and around 0.4 kgCO_2-eq./kWh for cogeneration. Greenhouse gas emissions from the nuclear chain and the renewable energy sources chains are two orders of magnitude below the emissions of fossil fuels chains. The UCTE average for nuclear is about 8 g of CO_2-eq./kWh, 5 g CO_2-eq./kWh for hydro, 11 g CO_2-eq./kWh for costal wind turbines, 14 g CO_2-eq./kWh for offshore wind turbines, 60 g CO_2-eq./kWh for PV (photovoltaics) [7] and 100 g CO_2-eq./kWh for wood cogeneration.

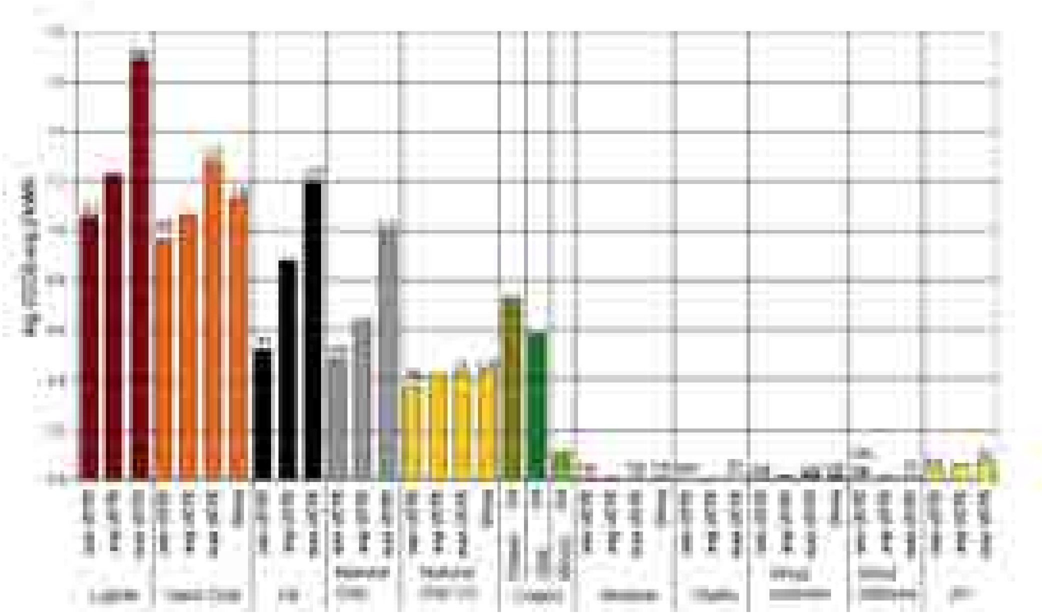

Figure 1: *CO_2 equivalent greenhouse gas emissions for each electricity production technology chains*

3.2 Other atmospheric emissions

While the greenhouse gas emissions have impacts on global warming and climate change, SO_X, and NO_X have more regional and local impacts. In addition, these pollutants are important also from regular point of view. There are SEVESO EU and national regulations and Environmental protection Act limiting the SO_X and NO_X emissions.

SO_2 emissions are dominated by the direct emissions from power plants. The level of emissions depends on the sulfur content of fuels and the emission control criteria. . As shown in Figure 2 brown coal and oil, with a UCTE average of around 7 g/kWh, have the highest level of SO_2 emissions. Hard coal has a UCTE average of about 3 g/kWh, while the chain of natural gas has a UCTE average of about 0.2 g/kWh emissions, which is the minimum between the chains of fossil fuels. The rate of SO_2 emissions in the nuclear chain and the renewable energy sources chains are more than two orders of magnitude below the emissions of fossil fuels chains. Hydro and wind have the lowest level of SO_2 emissions among renewable energy sources chains.

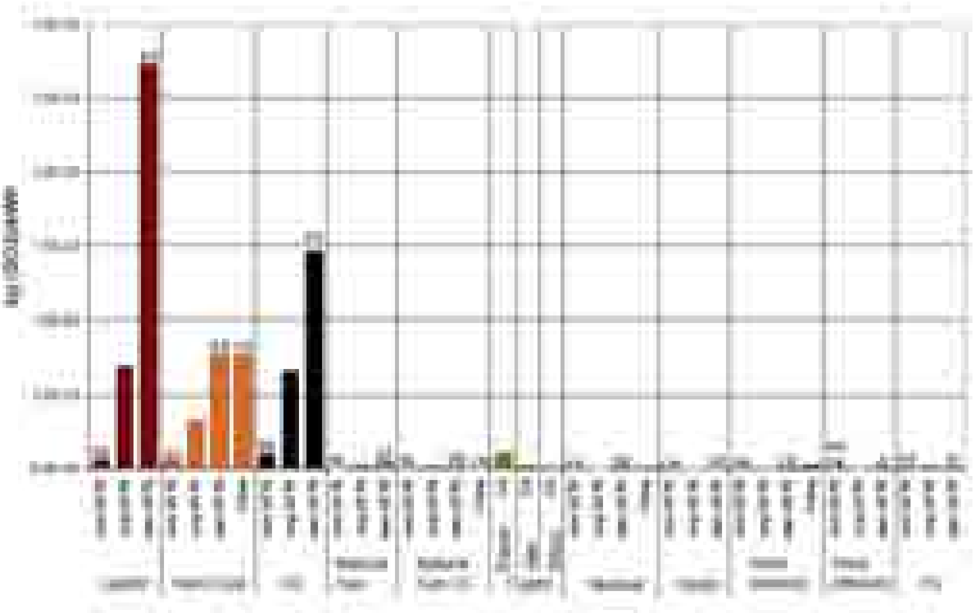

Figure 2: *SO_2 emissions for each electricity production technology chains*

Oil has the highest level of NO_X emissions of all the energy chain, with the UCTE average at around 2.8 g/kWh (see Figure 3). Levels of NO_X emissions from coal-chains are slightly lower, with the UCTE average of around 2.2 g/kWh. The chain of natural gas has the lowest level of NO_X emissions among fossil systems with a UCTE average of around 0.7 g/kWh. The level of NO_X emissions for nuclear, hydro and wind technology is up to two orders of magnitude lower than the rate of fossil fuels NO_X emissions.

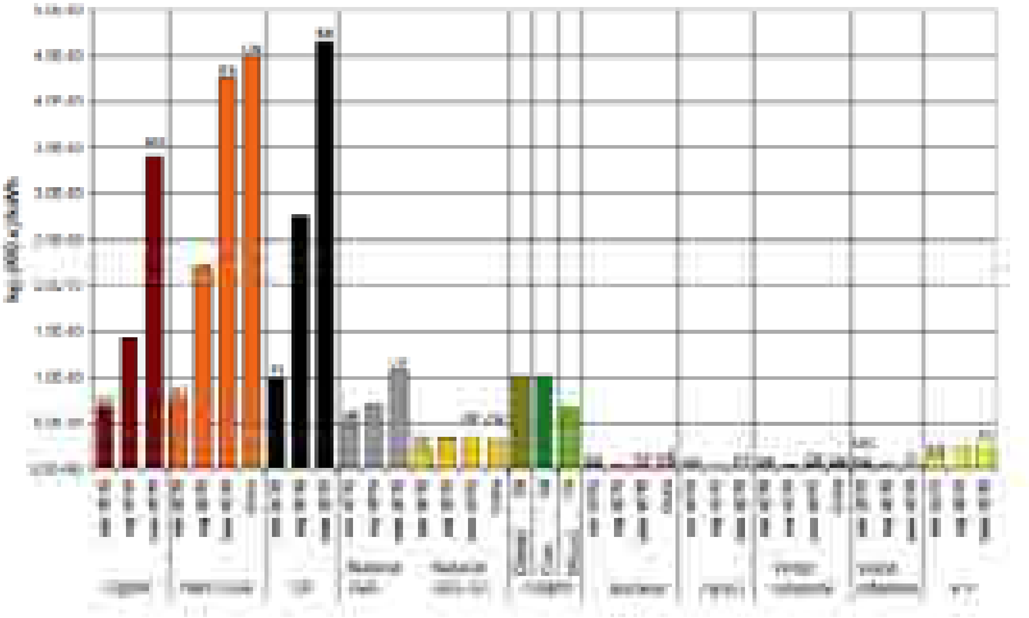

Figure 3: ***NO_x** emissions for each electricity production technology chains*

3.3 Non-radioactive waste

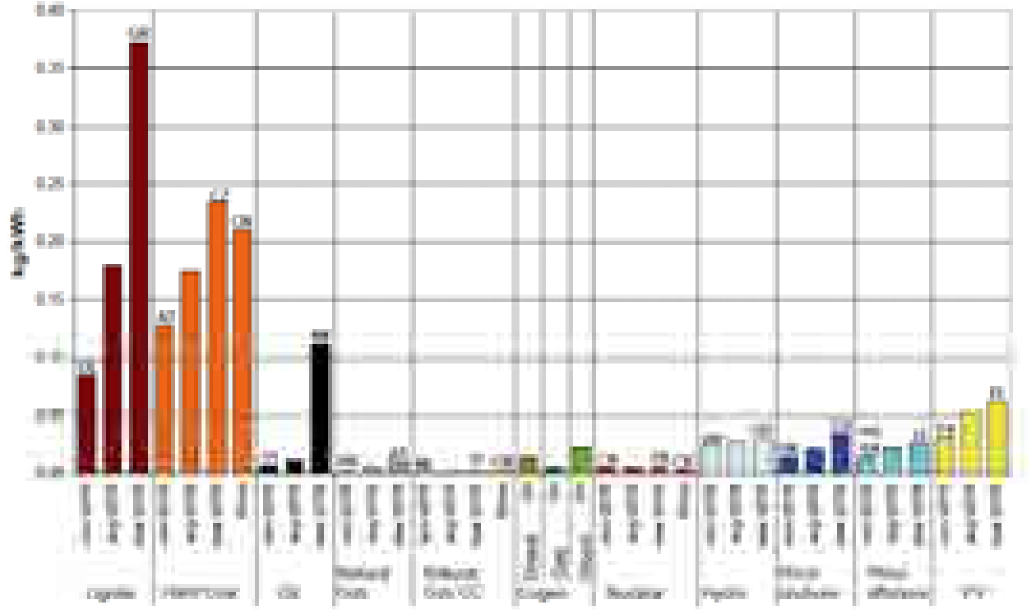

Figure 4: *Production of non-radioactive waste for different energy chains*

Production of non-radioactive waste for different energy chains is shown in Figure 4. Hard coal and lignite power chains produce the largest quantities of non-radioactive waste with UCTE averages of around 1.18 kg/kWh. Within the lignite chain, a major contribution is ash produced during power plant operation, while within hard coal chains a substantial proportion of the waste comes from excavation. The natural gas and nuclear chains produce a minimum quantity of non-radioactive waste. The amount of non-radioactive waste in hydro and wind chains is two orders of magnitude higher than for the nuclear chain.

3.4 Land use

Land use, shown in Figure 5, is measured in m^2/kWh and refers to areas which are modified from natural or primary habitat to different habitat states as a result of human intervention inside the whole energy chain.

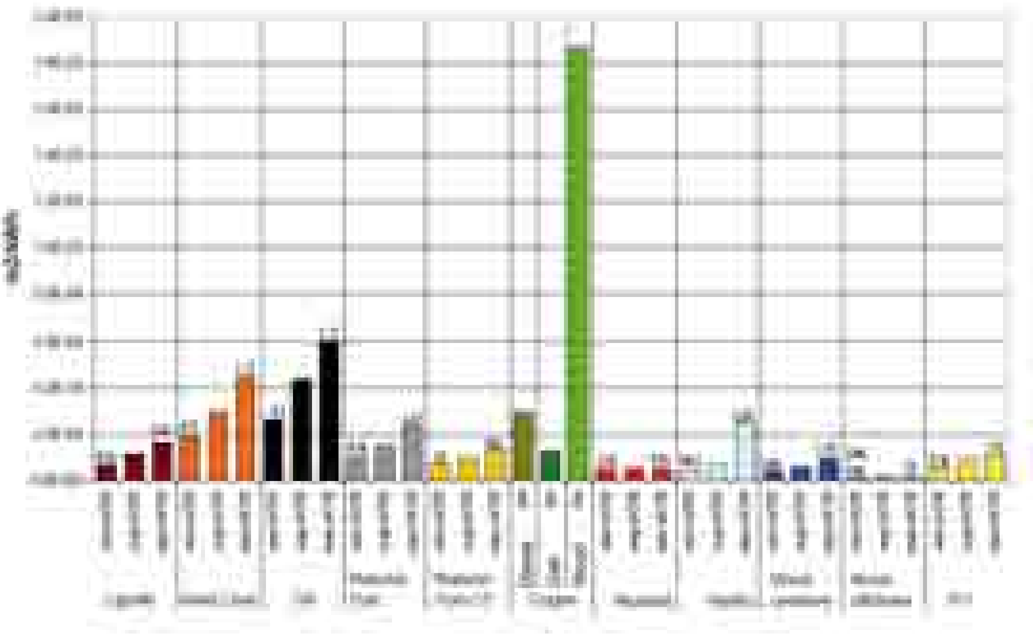

Figure 5: *Land use for different energy chains*

Due to the forestry and logging that are required for the use of biomass, wood cogeneration requires the largest land use, followed by coal and oil energy chains. Exploitation and production of oil, as well as the extraction of hard coal, require considerable space.

3.5 Accident risks

The data are derived from a comprehensive severe accidents databases, ENSAD (the Energy-related Severe Accident Database), with an emphasis on the energy sector. Databases enable a comprehensive analysis of accidents risks, which are not limited to electricity power plants but cover the entire energy chain, including exploration, extraction, processing, storage, transport and waste management.

ENSAD currently contains 18,400 accidents, of which approximately 89% occurred between 1969 and 2000. Human causes of accidents represent 70% of all accidents, while natural disasters represent 30%. All accidents related to energy representing 35% of all accidents and 50% of human caused accidents. Among the energy-associated accidents, the share of severe accidents is 49%, among which 67% accidents are with five or more fatalities. Accidents that are not related to energy and natural disasters have secondary importance within ENSAD. More detailed data can be seen in Table 1.

Table 1: *ENSAD report overview for accidents with at least five fatalities for period from 1969 to 2000*

Energy chain	OECD		EU15		non-OECD	
	Accidents	*Fatalities*	*Accidents*	*Fatalities*	*Accidents*	*Fatalities*
Coal	75	2,259	11	234	102 1,044 (a)	4,831 18,017(a)
Oil	165	3,789	58	1,141	232	16,494
Natural gas	80	978	24	229	45	1,000
LPG	59	1,905	19	515	46	2,016
Hydro	1	14	0	0	10	29,924 (b)

a)First line without China, second line with China
b)Banqiao and Shimantan dam failures together caused 26,000 fatalities

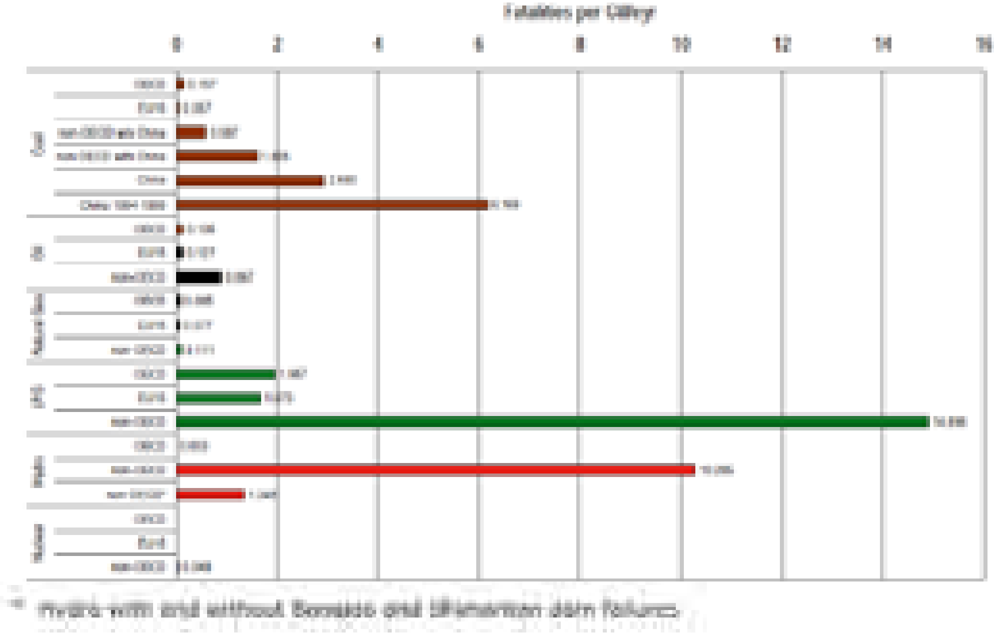

Figure 6: *Severe accidents indicators for OECD and non–OECD countries for period from 1969 to 2000*

China has exceptional accidents statistic for hydro as the result of the Banqiao and Shimantan dam failures, which occurred in 1975. Both dams were broken as a result of construction and engineering errors, which became critical during a huge flood in 1975. As a result of these two dam failures, 62 dams were destroyed flooding an area of 55 km by 15 km. Some reports indicate the total numbers of fatalities are somewhere between 90,000 and 230,000 [3].

Figure 6 represents the fatalities normalized to the unit of energy produced per GWe year. The highest value of fatalities was caused by LPG energy chain, due to the danger of handling LPG. The second highest value is with the hydro energy chain due to the above-mentioned Banqiao and Shimantan dam failures. The coal energy chain is on third place due to the mining process, which is especially dangerous in China, where safety is at low level. Values for OECD and EU15 member states are almost the same for the selected technology chain due to the higher safety culture level.

3.6 Human health impacts from normal operation

Effects on human health in relation to the normal operation can be represented by mortality. Mortality is defined as a reduction of expectations of life, expressed in terms of years of life lost (YOLL). The consequences of diseases could be evaluated, but it is difficult to combine in a completely objective manner, because the end result, years of life lost, and population values, provided by monetary relations change dramatically depending on local conditions, density of the population, the prospect of life expectancy and the medical assistance that is available for the affected population. Figure 7 shows an example of mortality that is the result of emissions of major pollutants, specific to the current German energy chains, also taking into account the radioactive emissions [8]. The methodology for assessment of health impacts was developed within the European ExternE project and later revised by Friedrich et al. [9] and Bickel and Friedrich [10].

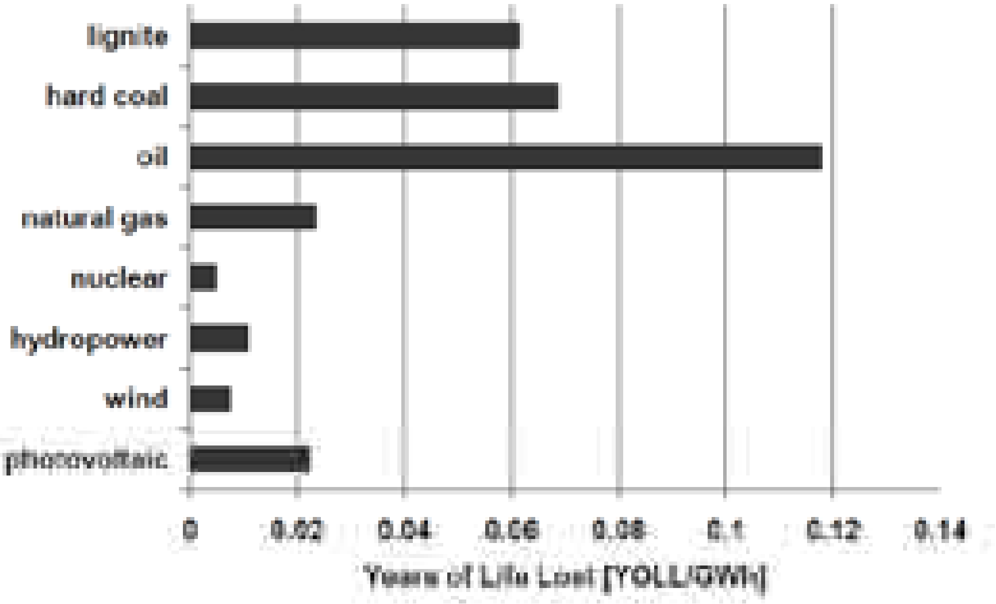

Figure 7: *Mortality associated with normal operation of German energy chains in the year 2000*

Nuclear, wind and hydro-energy chains have low mortality in relation to their normal operation. The mortality for natural gas and solar PV chains are comparable. Fossil systems other than natural gas indicate a greater impact than other options. Mortality due to air pollution is strongly dependent on the location, which determines the number of people affected by the emissions and the technology, which will determine the quantity of emissions. The figure for YOLL per ton of SO_2 released in China is on average almost seven times higher than the average of the European Union, mainly due to drastic differences in population density around the plants.

3.7 Use of energy resources

Fossil resources have been selected as an indicator of energy product use due to their lack of stock and usefulness within other sectors. This has a direct impact on the long-term energy sustainability, if we intend to preserve resources for chemical and other uses, and not just for energy.

The consumption of fossil fuels for electricity production different chains are given in Figure 8 and covers the member states of UCTE and some other European countries.

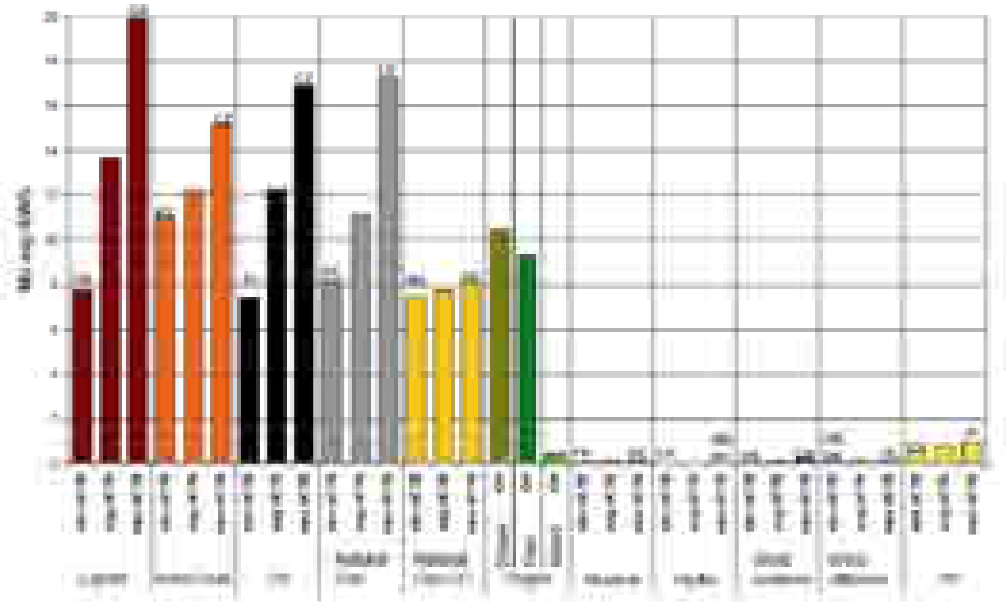

***Figure-8:** Requirements of fossil resources for different energy chains*

Consumption is, of course, much greater in the fossils, coal, gas and oil chains, than in the case of nuclear and renewable energy sources chains. Chains with combined gas power plants have the lowest consumption of fossil chains, which is expected due to their effectiveness. Renewable energy sources and nuclear chains indirectly use fossil fuels for heat and electricity consumption within their chains. Hydro energy has the lowest consumption of fossil fuels.

3.8 Use of non-energy resources

Usage of other non-renewable resources such as fossil fuels and uranium is the measurement of electricity production impact to the environment, and therefore is included in economic indicators. Copper was selected as the reference material for the limited metal resources, but the consumption of other materials could also be used. Figure 9 shows the comparison of copper needs for various electricity types of production in UCTE countries. Solar panels or PV shows the highest need for copper, which exceeded the needs of the other chains by a factor of five; solar is followed by the wind energy chain. Chains of fossil fuels, nuclear, and wood cogeneration have comparable needs for copper, which are lower by a factor of 10 compared to PV. Hydro energy shows the lowest requirements for copper.

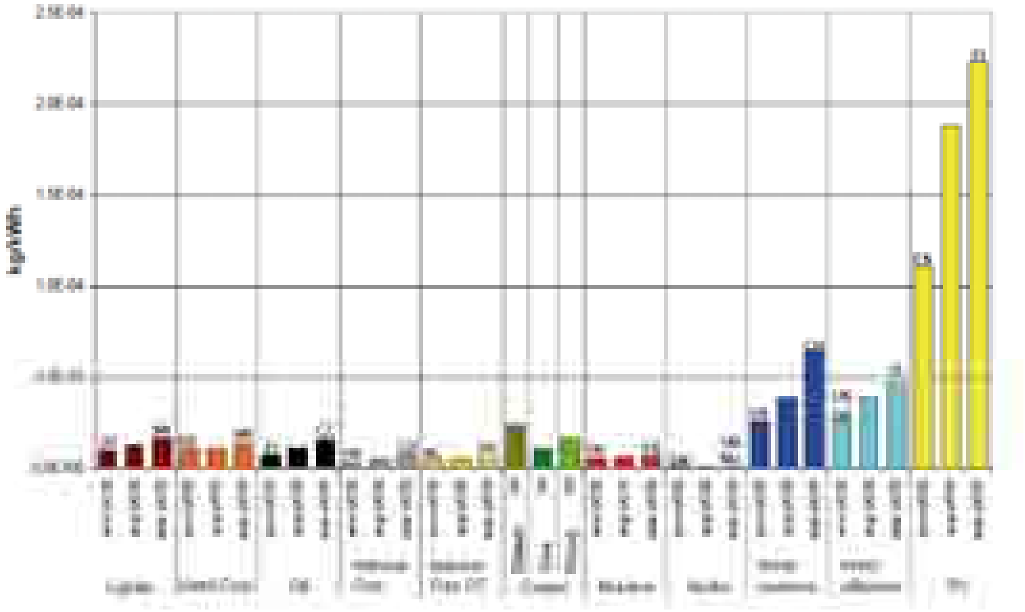

Figure 9: *Requirements of copper for different energy chains*

4 ENVIRONMENTAL IMPACTS OF DIFFERENT ENERGY TECHNOLOGY OPTIONS FOR ELECTRICITY PRODUCTION IN SLOVENIA

Slovenia is in the decision-making process for its future energy production sector development. The decision for a specific technology must be based on facts derived by environmental impact comparisons like the OECD studies, as indicated above. Therefore, GEN energija has ordered a widened environmental impact assessment study with comparisons of different technology options for electricity production in Slovenia.

This study was done by URS's team of environmental experts. The basic position was the technology is available in Slovenia and, if possible to be located with a range of 10 km around

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the existing nuclear power plant. The objectives for each technology options were the production of electricity with a power of at least 1,000MWe at 90% baseload capacity factor.

It was found that suitable technology options for Slovenia are those which already exist and these are nuclear, gas, coal and hydro. The proposed renewable energy technologies beside hydro were wind, solar, geothermal and biomass. In the process of technological comparison, nuclear technology is based on the III / III + generation nuclear power plants, which are commercially available on the market. These are Atmea's ATMEA-1, Areva's EPR, Westinghouse's AP-1000 and Mitsubishi's APWR.

Unlike nuclear power plants, which are commercially available, the process of comparison included commercially inaccessible CCS technology for gas and coal technologies.

For renewable energy technologies, environmental impacts are evaluated for the entire area of Slovenia as a result of greater land use and dependence on the availability of the source. For comparison, a mixture of renewable energy sources technologies were generated, with a composition of 32% hydro, 36% wind and 32% biomass.

Impacts on the environment include a comparison of the effects for the entire area of the environment, for areas that are standard in all international comparison analysis and evaluations of environmental impacts. Impacts on the environment are divided into 14 areas, presented in Figure 10.

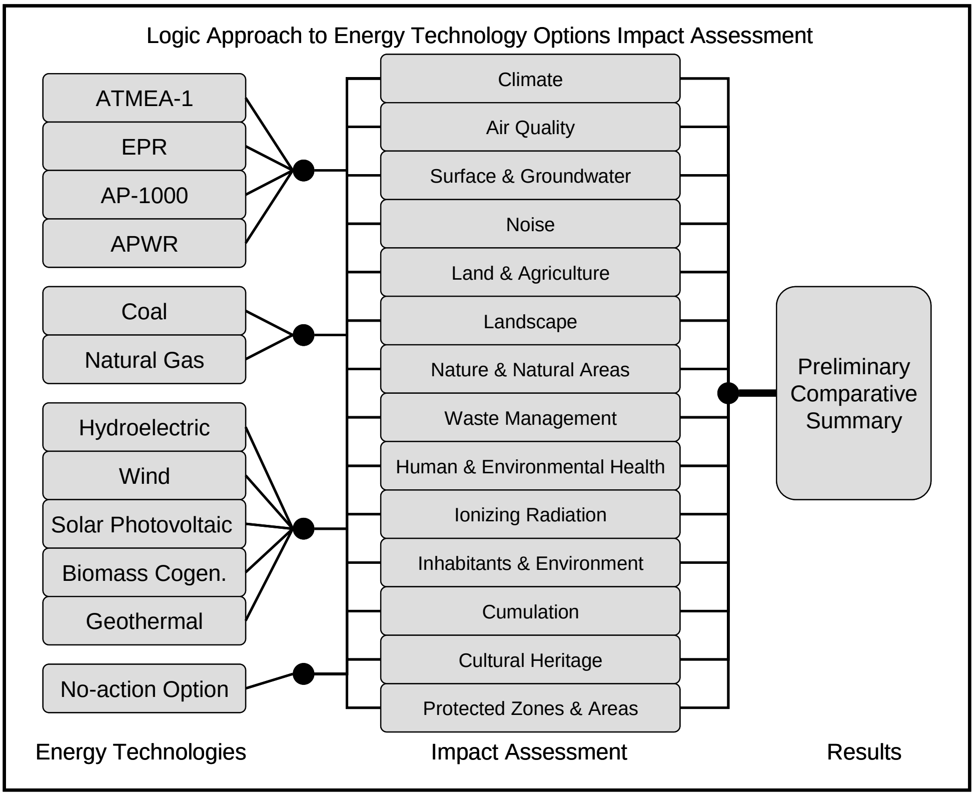


Figure 10: *Energy technology options impact assessment*

The evaluated environmental impact assessment areas in the study are climate, air quality, surface and ground water, noise, land and agriculture, landscape, nature and natural areas, waste management, human and environmental health, ionizing radiation, inhabitants and environment, accumulation, cultural heritage, protected zones and areas. These assessment areas were evaluated by six different level of impact: A – with no impact or positive impact, B – insubstantial impact, C - insubstantial impact with mitigation, D – substantial impact, E – destructive impact and X – establishing impact was not possible. See Table 2 for details.

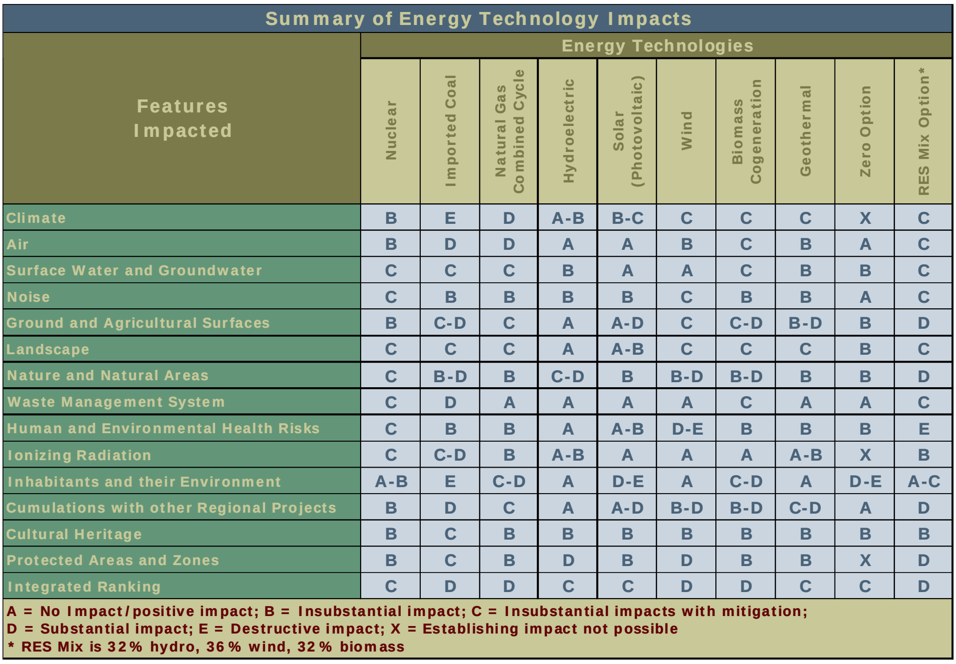
5 RESULTS OF ENVIRONMENTAL IMPACTS FOR DIFFERENT TECHNOLOGY OPTIONS FOR SLOVENIA

For a mixture of renewable sources, it was found that with an installed power 1000MWe, they are not able to ensure a baseload capacity factor of 90% but only 34%, taking into account the whole area of Slovenia. To achieve the same effects, as the baseload electricity producer with an installed capacity 1000MWe and an availability factor of 90%, it is required to install 3000MWe through renewable energy sources. The already-proposed installed 1000MWe for renewable energy sources is an optimistic goal for the entire area of Slovenia, since all the potentials due to the current environmental protected areas cannot be exploited.

Table 2 shows both the intermediate results for each area of comparison as well as the final assessment for each technology. Nuclear technology has an insubstantial impact on the environment and is comparable to hydro, PV and geothermal technology. Gas, coal, wind and biomass technologies have a substantial impact on the environment. The mixture of renewables that have been selected for comparison have the same impact.

Among the evaluated and compared technologies with grade insubstantial impact, nuclear option is the only baseload producer in Slovenia whose production can be expanded.

Table-2: *Summary of energy technology impacts*



Summary of Energy Technology Impacts

Features Impacted	Nuclear	Imported Coal	Natural Gas Combined Cycle	Hydroelectric	Solar (Photovoltaic)	Wind	Biomass Cogeneration	Geothermal	Zero Option	RES Mix Option*
Climate	B	E	D	A-B	B-C	C	C	C	X	C
Air	B	D	D	A	A	B	C	B	A	C
Surface Water and Groundwater	C	C	C	B	A	A	C	B	B	C
Noise	C	B	B	B	B	C	B	B	A	C
Ground and Agricultural Surfaces	B	C-D	C	A	A-D	C	C-D	B-D	B	D
Landscape	C	C	C	A	A-B	C	C	C	B	C
Nature and Natural Areas	C	B-D	B	C-D	B	B-D	B-D	B	B	D
Waste Management System	C	D	A	A	A	A	C	A	A	C
Human and Environmental Health Risks	C	B	B	A	A-B	D-E	B	B	B	E
Ionizing Radiation	C	C-D	B	A-B	A	A	A	A-B	X	B
Inhabitants and their Environment	A-B	E	C-D	A	D-E	A	C-D	A	D-E	A-C
Cumulations with other Regional Projects	B	D	C	A	A-D	B-D	B-D	C-D	A	D
Cultural Heritage	B	C	B	B	B	B	B	B	B	B
Protected Areas and Zones	B	C	B	D	B	D	B	B	X	D
Integrated Ranking	C	D	D	C	C	D	D	C	C	D

A = No Impact/positive impact; B = Insubstantial impact; C = Insubstantial impacts with mitigation;
D = Substantial impact; E = Destructive impact; X = Establishing impact not possible
* RES Mix is 32% hydro, 36% wind, 32% biomass

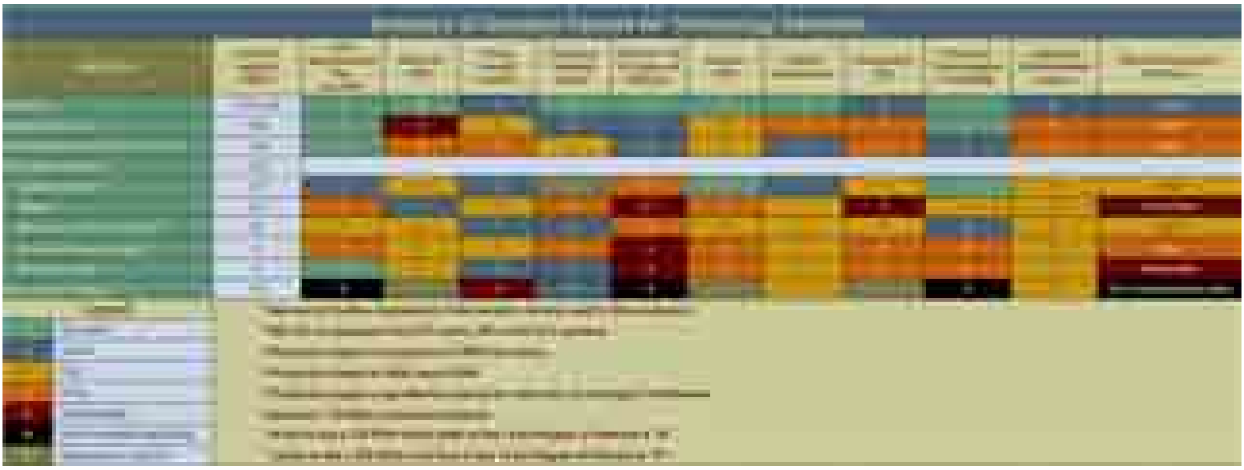
The summary table (Table 3) of the site-specific decision factors was used for assessing and ranking the relative feasibility and desirability of the four primary energy technology options evaluated in the study.

The summary table decision factors are land requirements per kWh, green house gases per kWh, energy supply security, baseload capacity factor, ability to locate in region of influence, cost per kWh, existing infrastructure, uncertainty risk, economic-technology feasibility, aggregate environmental impacts. All these decision factors were evaluated according to seven different rankings: X - excellent, G - good, F - fair, P - poor, U - undesirable, N - not available or not applicable and S – where was source depended.

Nuclear technology is evaluated as the most optimal technology for the expansion of production capacities in Slovenia.

Renewable energy sources, whose potential in Slovenia is already heavily utilizing, are estimated to be fair to undesirable and can serve only as complementary technologies to the basic scenario for the expansion of production capacity.

Table 3: *Summary of decision factors for technology selection*



6 CONCLUSION

The decision-making process for short and long term energy future solutions should be based on solid environmental impacts comparisons.

GEN energija ordered the presented comparative study to substantiate its business purposes and the decisions, but the main purpose is to convince all who are involved in the decision-making processes of how the future development of energy for Slovenia should entitled the environmental, economic and sustainable point of view.

Nuclear technology is at the top of the environmental acceptability on the global scale, as shown by the OECD studies, as well locally, which has shown by the URS-GEN study. From an environmental point of view, nuclear energy is one of the optimal technology choices for Slovenia, while in combination with other decision-making factors it becomes the most optimal. It is also the only baseload electricity producer, whose installed power can be increased almost without any impact to the environment, as evidenced by the study. In addition to baseload electricity production, new nuclear power plants are also capable of operating in load follow production. By increasing the share of nuclear energy in final energy consumption, Slovenia could also greatly reduce greenhouse gas emissions and could achieve the EU and national targets for reducing such emissions.

If Slovenia wants to stay environmentally conscious, if wants to keep or even increase the competitiveness of the economy and meet the requirements of sustainable development, nuclear energy is the optimal solution for the future.

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MATHEMATICAL MODEL OF THE POWER SUPPLY SYSTEM CONTROL

MATEMATIČNI MODEL UPRAVLJANJA ENERGETSKEGA SISTEMA

Janez USENIK$^{\Re}$

Keywords: power supply system, control, optimal energy capacities, Laplace transform, fuzzy logic;

Abstract

In this article, a simple mathematical model of a continuous stochastic power supply system is described. Some analytical approaches have been developed to describe the influence of production and stock, i.e. additional capacities on a hierarchical spatial pattern and demand. Using the Laplace transform, it is possible to solve the system of differential equations, which are represented with the continuous model. Due to the stochastic nature of system inputs, the optimality criteria with the Wiener filter are satisfied. The inverse Laplace transform is calculated with residues in the complex space. Furthermore, an interesting and efficient approach with fuzzy logic is used, which is presented at the end of this article.

Povzetek

V članku je predstavljen matematični model upravljanja zveznega stohastičnega energetskega sistema. Razviti so nekateri analitični pristopi, s katerimi opišemo medsebojni vpliv proizvodnje ter zalog, v takšnih sistemih so to dodatne kapacitete, na hiearhično porazdeljeno prostorsko dogajanje/porabo oziroma povpraševanje. Z uporabo Laplaceove transformacije rešimo sistem diferencialnih enačb, ki opisujejo dinamiko zveznega sistema. Pogoju optimalnosti lahko zaradi stohastičnih vhodov sistema zadostimo z uporabo Wienerjevega filtra. Inverzno Laplaceovo transformacijo opravimo z uporabo residuov. V nadaljevanju članka prikažemo še kot izjemno zanimiv in zlasti zelo učinkovit način pristopa k reševanju takšnega problema tudi možnost uporabe mehke logike.

$^{\Re}$ Corresponding author: Prof. Janez USENIK, PhD., University of Maribor, Faculty of Energy Technology, tel. +386 31 751 203, Fax: +386 7 620 2222, Mailing address: Hočevarjev trg 1, 8270 Krško, e-mail address: janez.usenik@uni-mb.si

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1 DEFINING THE PROBLEM

Every model of optimal control is determined by a system, input variables and the optimality criterion function. The system represents a regulation circle, which generally consists of a regulator, a control process, a feed-back loop, and input and output information (DiStefano, 1987). In this article, we will only discuss linear dynamic stationary continuous systems (Usenik et all, 2008). The optimality criterion is the standard against which the control quality is evaluated. The term “control quality” means optimal and synchronized balancing of planned and actual output functions.

Let us consider a production model in a linear stationary dynamic system in which the input variables indicate the demand for products manufactured by a company. These variables, i.e. the demand in this case, can be a one-dimensional or multi-dimensional vector function on the one hand and deterministic, stochastic or fuzzy on the other. In this article, stochastic variables and an outline of a fuzzy approach are presented.

Let us take a stationary random process X with the known mathematical expectation $E(X)$ and autocorrelation $R_{XX}(t)$ as the demand in a stochastic situation that should be met, if possible, by the current production. The difference between the current production and demand is the input function for the control process, the output function of which is the current stock/additional capacities. When the difference is positive, the surplus will be stocked and when it is negative, the demand will also be covered from stock. Of course, in the case of power supply we do not have stock in the usual sense (such as in car or computer etc.); energy cannot be produced in advance for a known customer nor can stock be built up for unknown customers. The demand of energy services is neither uniform in time nor known in advance. It varies, has its ups (peaks) and downs (minima) and it can only be met by installing and activating additional proper technological capacities. Because of this, the function of stock in the energy supply process belongs to all the additional technological potential/capacities, large enough to meet periods of extra demand. The demand of energy services is not given and precisely known in advance. With market research, we can only learn about the probability of our specific expectations of intensity of demand. The demand is not given with explicitly expressed mathematical function; we only know the shape and type of the family of functions. Demand is, according to these facts, a random process for which all the statistical indicators are known.

The system input represents the demand for the products/services that a given subject offers. Let demand be a stationary random process with two known statistical characteristics: mathematical expectation and autocorrelation function (Usenik, 2001). Any given demand should be met with current production. The difference between the current capacity of production/services and demand is the input function for the object of control. The output function measures the amount of unsatisfied costumers or unsatisfied demand in general. When this difference is positive, i.e. when the power supply capacity exceeds the demand, a surplus of energy will be made. When the difference is negative, i.e. when the demand surpasses the capacities, extra capacities will have to be added or, if they are not enough, extra purchasing from outside will have to be done. Otherwise, there will be delays, queues etc. In the new cycle, there will be a system regulator, which will contain all the necessary data about the true state and which will, according to given demand, provide basic information for the production process. In this way, the regulation circuit is closed (Fig. 1). With optimal control we will understand the situation in which all costumers are satisfied with the minimum

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involvement of additional facilities. On the basis of the described regulation circuit, we can establish a mathematical model of power supply control, i.e. a system of differential equations for continuous systems (Bogataj, Usenik, 2005) in our situation.

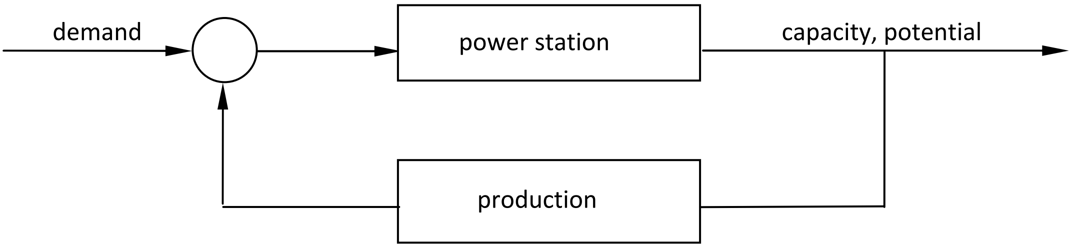

Figure1: *Regulation circuit of the power supply system*

The task is to determine the optimum production and stock/capacities, so that the total cost will be as low as possible.

2 EQUATIONS OF THE MODEL

Notations for $t \geq 0$ are as follows:

$Z(t)$ - additional capacities (stocks) at a given time *t*,

$u(t)$ - production at time *t*,

$d(t)$ - demand for product at time *t*,

λ - lead time

Let $Z(t)$, $u(t)$ and $d(t)$ be stationary continuous stationary random variables/functions; they are characteristics of continuous stationary random process.

Now the system will be modelled with the known equations:

$$\dot{Z}(t) = v(t) - d(t) \tag{2.1}$$

$$v(t) = u(t - \lambda) \tag{2.2}$$

$$u(t) = -\int_0^t G(\tau) Z(t - \tau) d\tau \tag{2.3}$$

In the equation (03) the function $G(t)$ is the weight of the regulation that must be determined at optimum control, so that the criterion of minimum total cost is satisfied. The parameter λ, named lead time, is the time period needed to activate the additional capacities in the power supply process. We used a real situation in which any goods can

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be sold to the customer only from the "storehouse of finished goods," because only in this case can the information flow of a company be updated and in accordance with legislation.

Assuming that the input variable demand is a stationary random process, we can also consider production and stock/additional capacities to be stationary random processes for reasons of the linearity of the system. Let us consider the functions $Z(t)$, $u(t)$ and $d(t)$ to be continuous stationary random processes.

Let us express the total cost, the minimum of which we are trying to define, with the mathematical expectation of the square of random variables $Z(t)$ and $u(t)$:

$$Q(t)=K_Z E\left(Z^2(t)\right)+K_u E\left(u^2(t)\right) \tag{2.4}$$

In (2.4) K_Z and K_u are positive constant factors, attributing greater or smaller weight to individual costs. Both factors have been determined empirically for the product and are therefore in the separate plant (Usenik, Bogataj, 2005).

Equations (2.1)-(2.4) represent a linear model of control in which we have to determine the minimum of the mean square error, if by means of a parallel shift we cause the ideal quantity to equal zero.

Functions of the system are normally transferred into the complex area by means of the Laplace transform. Let be **L** Laplace operator and $Z(s)$, $D(s)$, $u(s)$, $v(s)$ Laplace transforms:

$$\begin{aligned} Z(s)&=\mathscr{L}\{Z(t)\}\\ D(s)&=\mathscr{L}\{d(t)\}\\ U(s)&=\mathscr{L}(u(t))\\ V(s)&=\mathscr{L}\{v(t)\} \end{aligned}$$

When now the Laplace transform is performed on the functions of the system (01)-(03), we obtain the expressions:

$$Z(s)=\frac{1}{s}\left[v(s)-d(s)\right] \tag{2.5}$$

$$v(s)=e^{-\lambda s}u(s) \tag{2.6}$$

$$u(s)=-G(s)Z(s) \tag{2.7}$$

n the simplified version the expressions are defined, as follows

$$D(s)=G_p(s)d(s) \tag{2.8}$$

$$V(s)=G_f(s)u(s) \tag{2.9}$$

$$G_f(s)=\tilde{G}_f(s)G_p(s) \tag{2.10}$$

$$W(s)=\frac{G(s)}{1+G(s)G_f(s)} \tag{2.11}$$

we may draw the flowchart in an usual cascade form (Figure 2).

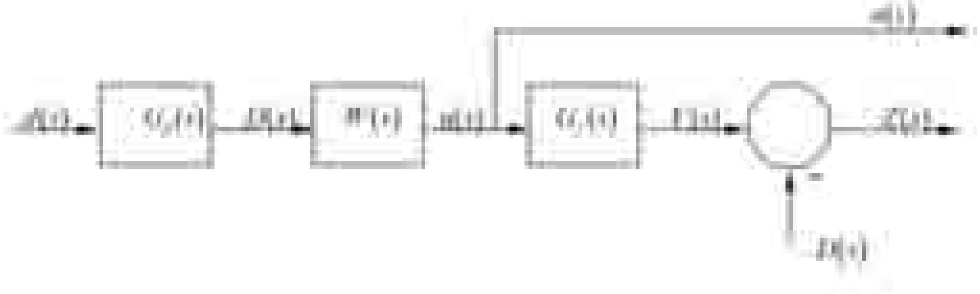

__Figure 2:__ The cascade flow-chart

The function (2.4), the minimum of which we are trying to determine, is written in accordance with the definition of the autocorrelation in the following form:

$$Q=K_Z R_{ZZ}(0)+K_u R_{uu}(0)$$

or, divided by $K_Z \neq 0$

$$P=R_{ZZ}(0)+A^2 R_{uu}(0)$$

$$P=\frac{Q}{K_Z} \tag{2.12}$$

$$A^2=\frac{K_u}{K_Z}$$

From Figure 2 we can see:

$$u(s)=W(s)D(s) \tag{2.13}$$

$$Z(s)=\left[W(s)G_f(s)-1\right]D(s) \tag{2.14}$$

Spectral densities from $R_{ZZ}(t)$ and $R_{uu}(t)$ are as follows:

$$\Phi_{ZZ}(s)=\mathscr{L}\left\{R_{ZZ}(t)\right\}=\int_0^\infty R_{ZZ}(t)e^{-st}dt=\left[W(s)G_f(s)-1\right]\cdot\left[W(-s)G_f(-s)-1\right]\Phi_{DD}(s) \tag{2.15}$$

$$\Phi_{uu}(s)=\mathscr{L}\left\{R_{uu}(t)\right\}=\int_0^\infty R_{uu}(t)e^{-st}dt=W(s)W(-s)\Phi_{DD}(s) \tag{2.16}$$

Both equations (2.15)-(2.16) are transformed in the real time space and inserted into the equation (2.12):

$$\begin{aligned} P &= R_{ZZ}(0) + A^2 R_{uu}(0) = \\ &= R_{DD}(0) - 2\int_{-\infty}^{\infty} W(t_1)dt_1 \int_{-\infty}^{\infty} G_f(t_2) R_{DD}(t_1+t_2)dt_2 + \\ &\quad + \int_{-\infty}^{\infty} W(t_1)dt_1 \int_{-\infty}^{\infty} G_f(t_2)dt_2 \int_{-\infty}^{\infty} W(t_3)dt_3 \int_{-\infty}^{\infty} G_f(t_4) R_{DD}(t_1+t_2-t_3-t_4)dt_4 \\ &\quad + A^2 \int_{-\infty}^{\infty} W(t_1)dt_1 \int_{-\infty}^{\infty} W(t_2) R_{DD}(t_1-t_2)dt_2 \end{aligned} \tag{2.17}$$

We are looking for the minimum of the equation (2.17). This optimum is obtained with the variation calculus:

$$W(t) = W_{opt}(t) + \xi W_\eta(t) \tag{2.18}$$

In (2.18), the function $W_\eta(t)$ is a variation of the function $W(t)$, ξ represents a variation parameter and $W_{opt}(t)$ is the optimal solution of (2.18). Function $W(t)=0$ for $t<0$. From (2.17) and (2.18), the Wiener-Hopf equation is derived

$$\begin{aligned} &\int_{-\infty}^{\infty} W_{opt}(t_3)dt_3 \left[\int_{-\infty}^{\infty} G_f(t_2)dt_2 \int_{-\infty}^{\infty} G_f(t_4) R_{DD}(t_1+t_2-t_3-t_4)dt_4 + A^2 R_{DD}(t_1-t_3) \right] - \\ &- \int_{-\infty}^{\infty} G_f(t_2) R_{DD}(t_1+t_2)dt_2 = 0 \text{ for } t_1 \geq 0 \end{aligned} \tag{2.19}$$

The second variation $\dfrac{d^2 P(\eta)}{d\eta^2}$ is obviously positive for every $t_1 \geq 0$ and the solution $W_{opt}(t)$ of the equation (2.19) is the minimum.

3 SOLUTION OF THE WIENER-HOPF EQUATION

The Wiener-Hopf equation (2.19) is solved by the spectral factorisation method (Schneeweiss, 1971). From (2.19) the Wiener-Hopf equation is obtained in the following form:

$$\int_{-\infty}^{\infty} W_{opt}(\tau)\Theta^+(t-\tau)d\tau - \pi^+(t) = 0 \text{ for } t \in (-\infty, \infty) \tag{3.1}$$

This equation is an ordinary integral equation of the first order, which can be solved by the Fourier/Laplace transform:

$$W_{opt}(s)\Theta^+(s) - \pi^+(s) = 0$$

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and finally

$$W_{opt}(s)=\frac{\pi^{+}(s)}{\Theta^{+}(s)} \tag{3.2}$$

The function $\Theta^{+}(s)$ has its zeros (i.e. poles of (3.2)) only on the left-side of the complex plane (s_1, s_2, s_3 in Figure 3). Similarly, the function $\Theta^{-}(s)$ has its zeros on the right-side of the complex plane (s_4, s_5, s_6 in Figure 3).

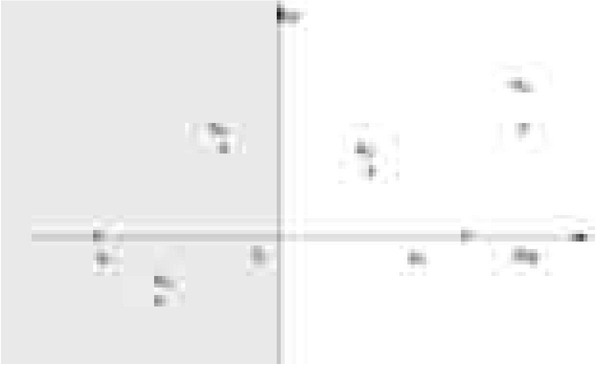

Figure 3: Poles of the function (21)

Also the function $\pi^{+}(s)$ has its poles only in the left half-complex plane, whereas $\pi^{-}(s)$ only in the right half-complex plane.

The optimal solution for the cascade operator is obtained in formal design by (3.2). The functions in the formula (3.2) are defined with expressions in the Laplace form:

$$\pi^{+}(s)=\left(\frac{G_f(-s)\Phi_{DD}^{+}(s)}{\left(G_f(s)G_f(-s)+A^2\right)^{-}}\right)^{+}$$

$$\Theta^{+}(s)=\left(G_f(s)G_f(-s)+A^2\right)^{+}\Phi_{DD}^{+}(s)$$

4 THE INVERSE LAPLACE TRANSFORM AND RESIDUES

The Laplace transform method solves differential equations and corresponding initial and boundary value problems. The solution of the subsidiary equation in the complex plane is transformed back to real plane to obtain the solution of the given problem. In the end, we determine the inverse transform $f(t)=\mathscr{L}^{-1}\{F(s)\}$, i.e. the solution of the problem. This is generally the most difficult step, and in it we may use the table of Laplace transforms or the residues (Kreyszig, 1999).

The purpose of the residue integration method is the evaluation of integrals $\oint_C f(s)ds$, taken around a simple closed path C. If *f(s)* is analytic everywhere on C and inside C, such an integral equals zero: $\oint_C f(s)ds=0$.

If *f(s)* has a singularity at the point $s=s_0$ inside C, but is otherwise analytic on C and inside C, the function *f(s)* assumes the Laurent series:

$$\begin{aligned} f(s)&=\sum_{k=0}^{\infty}a_k(s-s_0)^k+\sum_{k=1}^{\infty}\frac{b_k}{(s-s_0)^k}= \\ &=a_0+a_1(s-s_0)+a_2(s-s_0)^2+a_3(s-s_0)^3+\cdots\cdots+\frac{b_1}{s-s_0}+\frac{b_2}{(s-s_0)^2}+\frac{b_3}{(s-s_0)^3}+\cdots \end{aligned} \tag{4.1}$$

that converges in all points near $s=s_0$ (except at s = s$_0$ itself), in some domain of the form $|s-s_0|<R,\ R>0$. The coefficient b_1 of the first negative power of this series is obtained by the formula

$$b_1=\frac{1}{2\pi i}\oint_C f(s)ds \tag{4.2}$$

We can use the formula (4.2) to evaluate the integral:

$$\oint_C f(s)ds=2\pi i b_1$$

Here we integrate counter-clockwise around the simple closed path containing $s=s_0$ in its interior, but no other singular points of *f(s)* on or inside C.

The coefficient b$_1$ is called the residue of *f(s)* at $s=s_0$ and is denoted by

$$\operatorname*{Res}_{s=s_0} f(s)=\frac{1}{2\pi i}\oint_C f(s)ds \tag{4.3}$$

Residue integration can be extended from the case of a single singularity to the case of several singularities within the contour C. This is the purpose of the residue theorem: Let f(s) be analytic inside a simple closed path C and on C, except for finitely many singular points s$_1$, s$_2$, …, s$_n$ inside C (Figure 4). Then the integral of f(s) taken counter-clockwise around C equals 2πi times the sum of the residues of f(s) at s$_1$, s$_2$, …, s$_n$.

$$\oint_C f(s)ds=2\pi i\sum_{j=1}^{n}\operatorname*{Res}_{s=s_j} f(s) \tag{4.4}$$

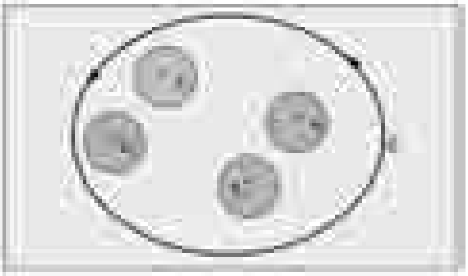

Figure 4: *The residue theorem*

The formula for the residue at a pole of any order is given by (Kreyszig, 1999):

$$\operatorname*{Res}_{s=s_k} f(s)=\frac{1}{(N-1)!}\lim_{s\to s_k}\left(\frac{d^{N-1}}{ds^{N-1}}\left[(s-s_k)^N f(s)\right]\right) \qquad k=1,2,3,\ldots \tag{4.5}$$

In this formula, *f(s)* has a pole of Nth order at $s=s_k$, and *n* is the number of all poles.

In particular, for a simple pole at $s=s_0$ the formula is:

$$\operatorname*{Res}_{s=s_0} f(s)=\lim_{s\to s_0}\left[(s-s_0)\,f(s)\right] \tag{4.6}$$

The residues will be used to compute the inverse Laplace transform:

$$f(t)=\mathscr{L}^{-1}\left\{F(s)\right\}=\frac{1}{2\pi i}\lim_{\omega\to\infty}\int_{c-i\omega}^{c+i\omega} F(s)e^{st}\,ds \tag{4.7}$$

In (4.7), we have to integrate over the line Re(s) = c. This line is based on the assumption that all the singularities (poles) of the function F(s) are on the left side of the line (Fig. 5).

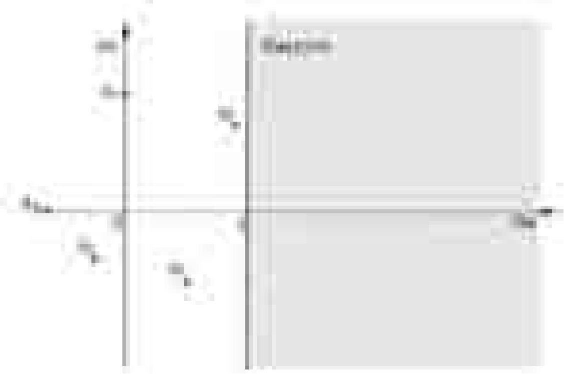

Figure 5: Integration over the line Re(s)=c

If we are to apply the residue theorem, we have to integrate over the counter-clockwise closed path $\Gamma(d)$. An integral taken over the line $\operatorname{Re}(s)=c$ is given as follows. We can describe a circle with the centre in the point 0 and with such a large radius *d* that all the singularities of the function f(s) are inside this circle (Figure 6)

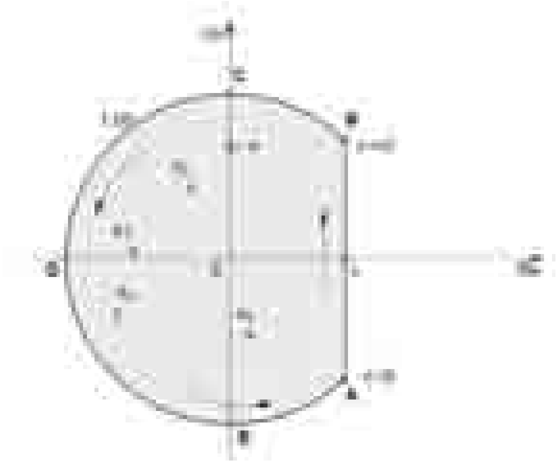

Figure 6: *Path* $\Gamma(d)$ *and the inside singularities of the function* $f(s)$

Following the residue theorem, we shall now write

$$\frac{1}{2\pi i}\int_{\Gamma(d)} F(s)e^{st}ds=\sum_{k}\operatorname*{Res}_{s=s_k}\left[F(s)e^{st}\right] \tag{4.8}$$

The integral over the path $\Gamma(d)$ is possibly divided in two parts: the integral over the line $\overline{AB}$ and the integral over the rest of the circle $\overline{BCDEA}$.

$$\oint_{\Gamma(d)} F(s)e^{st}ds=\int_{\overline{AB}} F(s)e^{st}ds+\int_{\overline{BCDEA}} F(s)e^{st}ds \tag{4.9}$$

Because the second integral in (4.9) equals zero, we get the following equation from (4.8) and (4.9):

$$\oint_{\Gamma(d)} F(s)e^{st}ds=\sum_{k}\operatorname*{Res}_{s=s_k}\left[F(s)e^{st}\right] \tag{4.10}$$

and the integral (28) equals the sum of the residues of $F(s)e^{st}$ at $s_1,s_2,s_3,\ldots,s_k$ to left of the line Re(s)=c:

$$f(t)=\mathscr{L}^{-1}\left\{F(s)\right\}=\frac{1}{2\pi i}\lim_{\omega\to\infty}\int_{c-i\omega}^{c+i\omega} F(s)e^{st}ds=\sum_{k}\operatorname*{Res}_{s=s_k}\left[F(s)e^{st}\right] \tag{4.11}$$

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5 AN EXAMPLE

For the problem (2.1)-(2.4), let the autocorrelation function of demand be known, for example:

$$R_{dd}(\tau)=e^{-|\tau|} \tag{5.1}$$

Comparing (2.5)-(2.7) with (2.8)-(2.10) we can write:

$$\begin{aligned} G_p(s)&=\frac{1}{s}\\ \tilde{G}_f(s)&=e^{-\lambda s}\\ G_f(s)&=\tilde{G}_f(s)\\ G_p(s)&=\frac{e^{-\lambda s}}{s} \end{aligned} \tag{5.2}$$

The spectral density of the given autocorrelation function is, as follows:

$$\Phi_{dd}(s)=\mathscr{L}\{R_{dd}(t)\}=\frac{2}{1-s^2} \tag{5.3}$$

From $D(s)=G_p(s)d(s)=\frac{d(s)}{s}$ we get

$$\Phi_{DD}(s)=-\frac{2}{s^2(s^2-1)}$$

and in the right half-plane

$$\Phi_{DD}^{+}(s)=\frac{1}{s(s+1)}$$

Due to

$$\left[G_f(s)G_f(-s)+A^2\right]^{-}=A-\frac{1}{s} \quad \text{and} \quad \left[G_f(s)G_f(-s)+A^2\right]^{+}=A+\frac{1}{s}$$

we can obtain the optimal cascade operator

$$W_{opt}(s)=\frac{s(Cs+1)}{As+1} \tag{5.4}$$

where

$$C=\frac{1+A-e^{-\lambda}}{1+A}$$

Now we can obtain the operator of the optimum regulation

$$G(s)=\frac{W_{opt}(s)}{1-W_{opt}(s)G_f(s)}=\frac{s(Cs+1)}{(As+1)-e^{-\lambda s}(Cs+1)}$$

in order to get:

a) the optimal production:

$$u_{opt}(s)=W_{opt}(s)G_p(s)d(s)=\frac{Cs+1}{(As+1)(s+1)} \tag{5.5}$$

b) the optimal stock/additional capacities:

$$Z_{opt}(s)=G_f(s)u_{opt}(s)-D(s)=\left[\frac{Cs+1}{As+1}e^{-\lambda s}-1\right]\cdot D(s) \tag{5.6}$$

With the inverse Laplace transform we obtain these functions in the time area.

a) the optimal production:

In formula (5.5), there are two single poles $s_1=-A^{-1}$ and $s_2=-1$ and consequently two residues:

$$\operatorname{Res}\left(s=-\frac{1}{A}\right)=\lim_{s\to-\frac{1}{A}}\left[\left(s+\frac{1}{A}\right)\frac{(Cs+1)e^{st}}{A\left(s+\frac{1}{A}\right)(s+1)}\right]=\frac{(A-C)e^{-\frac{t}{A}}}{A(A-1)}$$

$$\operatorname{Res}(s=-1)=\lim_{s\to-1}\left[(s+1)\frac{(Cs+1)e^{st}}{A\left(s+\frac{1}{A}\right)(s+1)}\right]=\frac{(1-C)e^{-t}}{(1-A)}$$

Consequently, the function in the real time space is, as follows:

$$u_{opt}(t)=\sum_{k=1}^{2}\operatorname*{Res}_{s=s_k}\left[F(s)e^{st}\right]=\frac{(A-C)e^{-\frac{t}{A}}}{A(A-1)}+\frac{(1-\alpha C)e^{-t}}{(1-A)}$$

and finally

$$u_{opt}(t)=\frac{1}{1-A}\left[\frac{C-A}{A}e^{-\frac{t}{A}}+(1-C)e^{-t}\right] \tag{5.7}$$

Similarly it is possible to obtain:

b) the production which reaches the storehouse with the delay of λ time units:

$$v(t)=u(t-\lambda)=\frac{(A-C)}{(1-A)}e^{-\frac{(t-\lambda)}{A}}-\frac{C-1}{A-1}e^{-(t-\lambda)} \tag{5.8}$$

c) the total demand in a given time interval with a variable upper limit:

$$D(t)=\mathscr{L}^{-1}\{D(s)\}=1-e^{-t} \tag{5.9}$$

d) the total optimal stock/additional capacities:

$$Z_{opt}(t)=M\left[e^{-\frac{(t-\lambda)}{A}}-Ke^{-t}\right] \tag{5.10}$$

where K and M are constants:

$$K=-\frac{C-1}{A-1}e^{\lambda} \quad \text{and} \quad M=\frac{C-A}{A-1}$$

6 FUZZY CONDITIONS

6.1 Fuzzy logic

Fuzzy logic is an innovative form of logic that allows a description of the desired system behaviour using spoken language. Many successful applications have been achieved not with conventional mathematical modelling but with fuzzy logic. As a theoretical mathematical discipline, fuzzy logic is designed to react to continuously changing variables and to challenge traditional logic by not being restricted to the conventional binary values of 0 and 1. Fuzzy logic allows the interpretation that something is not only “true” or “false,” but is also applicable to partial or multi-valued truths. This discipline is especially useful with problems that cannot be simply represented by classical mathematical modelling for reasons of incomplete data or an overly complex process. Statements using subjective categories have a major role in the decision making processes of the humans. The contents of these statements may be quantitative, uncertain, imprecise or ambiguous, but people can use them successfully for complex evaluations.

A mathematical model is required to implement the human logic into engineering solutions. Fuzzy logic makes the representation of the human decision and evaluation processes possible in algorithmic form. Fuzzy logic operates with terms such as fuzzy set, fuzzy variable, fuzzy number, fuzzy relation, fuzzy reasoning etc. A classical Boolean or binary logic is based on two crisp extremes: yes-now. Yes or now is an answer beyond doubt. The set in this case is defined by crisp boundaries, where an element is either a member of some crisp set or it is not, or its membership can be represented with the special function whose values are 0 or 1. Fuzzy logic, however, has unclear threshold. Fuzzy set is not defined by crisp boundaries, some elements are members with membership 1, some elements are members with membership 0, but certain elements can also be “more or less” members of this set an their membership can be between 0 and 1. Membership mapping the objects onto the unit interval [0, 1]. The degree of

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membership in a fuzzy set, for example named *A*, is expressed by a continuous function, called the membership function $\mu_A(x)$.

The combination of imprecise logic rules in a single control strategy is called approximate or fuzzy reasoning. Thus, the fuzzy inference is the process of mapping from a given input to an output, using fuzzy logic. Generally, there are five parts of the fuzzy inference process: fuzzification of the input variable, application of the fuzzy operator (and/or) in the antecedent, implication from the antecedent to the consequent, aggregation of the consequents across the rules, and finally, defuzzification (Ross, 2007).

In fuzzy logic, different values of a given linguistic variable represent concepts, not numbers. Linguistic values or terms associated with the linguistic variable “PRICE” can be obtained by specific fuzzy sets like “LOW”, “MEDIUM, “HIGH” etc. A technical quantity “PRICE” is measured with numbers (crisp value), for example 1,000 EUR. In contrast, the fuzzy approach uses terms, not numbers. Each fuzzy set like “LOW” or “MEDIUM” or HIGH is formed by its membership function. This function represents a certain degree to which a crisp value belongs to a given fuzzy set. From experience, we know that a price of 10 EUR or 20 EUR is “LOW”, a price of 1,000 EUR or 5,000 EUR is “HIGH”, but 10 EUR is less than 20 EUR, so the degree of membership of the fuzzy set “LOW” for the crisp number 10 is greater than for the crisp number 20. The procedure of transformation crisp numbers into fuzzy terms is called fuzzification. A single fuzzy rule assumes the form:

if x *is SET_A, then y is SET_B,*

where SET_*A* and SET_*B* are linguistic values defined by fuzzy sets in the universes of discourse *X* and *Y,* respectively. The *if* part of the rule is called the antecedent or premise, while the *then* part is called the consequent or conclusion. The variables x and *y* are defined on the sets *X* and *Y*.

The output of the fuzzy process can be the logical union of two or more fuzzy membership functions defined in the universe of discourse of the output variable. Defuzzification is the conversion of a given fuzzy quantity to a precise crisp quantity. In literature, at least seven methods (Ross, 2007) are common for defuzzifying: max-membership principle, centroid method, weighted average method, mean-max membership, centre of sums, centre of the largest area, first (last) of maxima.

6.2 Fuzzy reasoning

In principle every system can be modeled, analyzed and solved by means of fuzzy logic. Due to the complexity of the given problem and the subjective decisions of customers, which are better described with fuzzy reasoning, it is advisable to introduce a fuzzy approach. Some basic solutions of the control problems using fuzzy reasoning were presented in the paper (Usenik, Bogataj, 2005). For some problems about the control of the power supply system, we propose fuzzy reasoning. It is obvious that decision makers, when solving everyday problems in control of systems, operate with fuzzy logic (Terano, 1992).

Our proposed fuzzy model will be based on these assumptions, whereby the usual five steps have to be taken: fuzzification of the input and output variables, application of the fuzzy operator in the antecedent, implication from the antecedent to the consequent, aggregation of the consequents across the rules, and defuzzification.

6.3 Fuzzification

In the fuzzification phase we have to define fuzzy sets for all fuzzy variables (input and output) and define their membership functions.

Let us assume for example that the demand d_i at the location z_j depends on a) the market area, b) the density of the area, c) price, d) season and d) uncertainty. The demand is in fact the basic variable, on which the behaviour of all retailers depends (Figure 7).

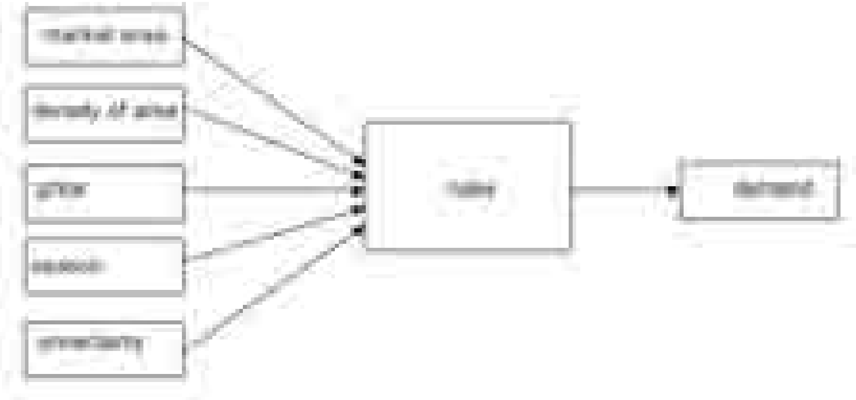

Figure 7: *Output fuzzy variable “demand” depends on 5 input fuzzy variables*

We assume that all expressions are fuzzy variables, market area, density of the area, price, season and uncertainty are input fuzzy variable, and demand is an output fuzzy variable. Every fuzzy variable is presented by more terms, for example:

a) input fuzzy variable MARKET AREA is represented by: SMALL, BIG,
b) input fuzzy variable DENSITY OF THE AREA is represented by: WEAK, MEDIUM, STRONG,
c) input fuzzy variable PRICE is represented by: LOW, MEDIUM, HIGH,
d) input fuzzy variable SEASON is represented by: LOW, HIGH,
e) input fuzzy variable UNCERTAINTY is represented by: SMALL, MEDIUM, BIG, VERY_BIG,
f) output fuzzy variable DEMAND is represented by: VERY_LOW, LOW, MEDIUM, HIGH, EXTREMELY_HIGH.

For every fuzzy set and for every fuzzy variable, we have to create membership functions. For the fuzzy variable DEMAND they could be as shown in Figure 8. On the x-axis, we measure the variable DEMAND given in units like kWh, MWh and so on, depending on our data. On the y-axis, we measure membership for every possible demand and for every fuzzy set VERY_LOW, LOW, MEDIUM, HIGH, EXTREMELY_HIGH.

Figure 8: Memberships functions of fuzzy sets for fuzzy variable PRICE

6.4 Fuzzy model

In our case we can define *n*-phase model with at least *n* rule blocks and *n* sets of input/output fuzzy variables (Fig. 9), (Usenik, 2009).

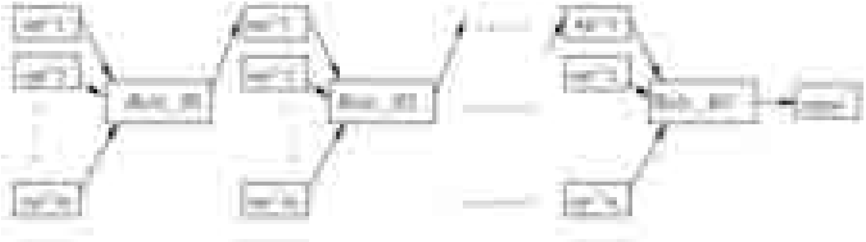

Figure 9: The structure of the fuzzy system

These fuzzy variables can solve the problem in general and can introduce quite a good starting point for further actions and steps to be taken in the process of decision-making. Due to the simplicity of this process, all membership functions will be of a simple triangular and trapezoidal shape. Of course, in further iterations and studies of market behaviour relevant for the customers' demands and requests, we shall state more sophisticated conditions to find answers to questions in real world situations.

6.5 Fuzzy rules inference

The computation of fuzzy rules is called fuzzy inference and consists of three steps: the application of the fuzzy operator (and/or) in the antecedent, the implication from the antecedent to the consequent and the aggregation of the consequents across the rules. The first step determines the degree to which the complete IF part of the rule is satisfied. In this step, we usually use the operator OR for the minimum and the operator AND for the maximum. The second step makes use of the support of the precondition to calculate the support of the consequence. Finally, the aggregation step determines the maximum degree of support for each consequence.

In our work, we applied FuzzyTech software (FuzzyTech, 2000). In accordance of this software tool, the rules were automatically created.

6.6 Defuzzification

The result from the evaluation of fuzzy rules is fuzzy. Defuzzification is the conversion of a given fuzzy quantity to a precise crisp quantity. The most frequently method used in praxis is CoM-defuzzification (the Center-of-Maximum). As more than one output term can be accepted as valid, the defuzzification method should be a compromise between different results. The CoM method does this by computing the crisp output as a weighted average of the term membership maxima, weighted by the inference results (Ross, 2007). CoM is a kind of compromise between the aggregated results of different terms *j* of a linguistic output variable and is based on the maximum *Yj* of each term *j*.

7 CONCLUSION

In this article, the model of the control of the power supply system has been presented, provided that the input functions (and for reason of linearity and stationarity, also an output function) were given as stochastic or fuzzy processes. On the basis of the specific items of the systems, the mathematical model of a system for the possibility of input/output functions being random processes was created and solved. In case of fuzzy conditions, demand and other functions were represented as fuzzy sets. In the future, research will have to be done in order to create a mathematical model of the power supply system for fuzzy conditions in general, shown in Fig. 8. One of the very interesting and highly realistic possibilities is the creation of the fuzzy model for solving or, better, predicting optimal energy capacities and technologies for permanent and reliable electricity supply, considering risk control (Fabijan, Predin, 2009). This research is part of the realization of that.

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THE CALCULATION OF THERMODYNAMIC PROPERTIES FOR HYDROCHLORIC AND COPPER COMPOUNDS IN A HYDROGEN PRODUCTION PROCESS

IZRAČUN TERMODINAMIČNIH LASTNOSTI V HIDROKLOROVIH IN BAKER KLOROVIH KOMPONENTAH V PROCESU PROIZVODNJE VODIKA

Jurij Avsec[1ℜ], *Greg F. Naterer*[2], *Andrej Predin*[1]

[1] University of Maribor, Faculty of Energy Technology,
Hočevarjev trg 1, 8270 Krško, SLOVENIA

[2] University of Ontario Institute of Technology, Oshawa, Ontario, Canada

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Abstract

Efficient and sustainable methods of clean fuel production are needed in all countries of the world in the face of depleting oil reserves and the need to reduce carbon dioxide emissions. With commitments for a hydrogen village, a hydrogen airport and a hydrogen corridor, the Canadian province of Ontario has already begun to move toward a hydrogen-fueled economy. However, a key missing element is a large-scale method of hydrogen production. As a carbon-based technology, the predominant existing process (steam-methane reforming (SMR)) is unsuitable.

ℜ Corresponding author: Assoc. Prof. Jurij Avsec, , Tel.: +386-7-620-2217, Fax: +386-2-620-2222, Mailing address: Hočevarjev trg 1, 8270 Krško, SLOVENIA
E-mail address: jurij.avsec@uni-mb.si

This paper focuses on a copper-chlorine (Cu-Cl) cycle, and the models of calculating thermodynamic properties. It discusses the mathematical model for computing the thermodynamic properties for pure substances such as H_2, CuCl and HCl, which are important in hydrogen production in their fluid phase, with the aid of statistical chain theory. The constants required make this computation, such as the characteristic temperatures of rotation, electronic state etc., and the moments of inertia are obtained analytically, by applying the knowledge of the atomic structure of the molecule. The procedures for calculating essential thermodynamic properties such as pressure, speed of sound, the specific heat, volumetric expansion coefficient, enthalpy and entropy are presented. To calculate the thermodynamic properties of Lennard-Jones chains, we have used the Liu-Li-Lu and Tang-Lu models. The thermodynamic properties of the Lennard-Jones mixtures are obtained using the one-fluid theory.

In recent years, thermodynamic theories based on statistical thermodynamics have been rapidly developed. Fluids with chain bonding and association have also received much attention. The interest in these fluids is due to the fact that they cover much wider range of real fluids than spherical ones. A good theory for these fluids will be very beneficial for chemical engineering applications, by reducing the number of parameters, and making them more physically meaningful and more predictable.

In technical practice, energy processes are of vital importance. In order to design devices in this field of activity, it is necessary to be familiar with the equilibrium and nonequilibrium thermodynamic properties of state in a one- and two-phase environment for pure refrigerants and their mixtures. To calculate the thermodynamic properties of real fluid, the Liu-Li-Lu (LLL) (revisited Cotterman) equation of state, based on simple perturbation theory and SAFT-VR equation of state for LJ chain fluid was applied. We developed the mathematical model for the calculation of all equilibrium thermodynamic functions of state for pure hydrocarbons and their mixtures.

In this paper, we have developed an analytical model based on the statistical thermodynamics and chain theory for pure components such as H_2, CuCl and HCl in the fluid region.

Povzetek

Toplogredni plini, ki nastajajo pri zgorevanju fosilnih goriv, predstavljajo veliko potencialno nevarnost za prihodnost obstoja človeka. Zaradi zmanjševanja emisije ogljikovega dioksida v ozračju in zaradi zmanjševanja zalog fosilnih goriv v svetu je potrebno preiti v prihodnosti na nove tehnologije pridobivanja goriv. Kanada je z razvojem vodikovih vasi, vodikovih letališč… že pričela z aplikacijo vodikovih tehnologij. V principu manjka za primer širokomasovne proizvodnje le metoda za pridobivanje vodika v velikih količinah.

Članek opisuje baker-klorov proces in termodinamične lastnosti v omenjenem procesu. V članku je prikazan model, kako izračunati termodinamične lastnosti komponent kot so vodik, CuCl in HCl. Omenjene komponente so zelo pomembne v proizvodnem procesu pridobivanja vodika. Omenjena metoda je povsem analitična in za določevanje termodinamičnih lastnosti uporablja statistično mehaniko in molekularno strukturo materialov.

Ta članek opisuje model izračuna termodinamičnih lastnosti, kot so na primer tlak, hitrost zvoka, specifične toplote, volumetrični ekspanzijski koeficient in entropija. V ta namen smo za izračun Lennard-Jonesovih verig uporabili Liu-Li-Lu-jev model. Termodinamične lastnosti zmesi so izračunane na osnovi eno- fluidne teorije. Predstavljen model predstavlja prvi tovrsten poskus v svetovni literaturi za izračun termodinamičnih veličin, ki se uporabljajo v baker-klorovem procesu.

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1 INTRODUCTION

Currently, the world consumes about 85 million barrels of oil and 104 trillion cubic feet of natural gas per day, releasing greenhouse gases that lead to global warming. In contrast, hydrogen is a clean energy carrier. Some have questioned whether the "hydrogen economy" is feasible in the near future or remains a distant ideal. However, the global hydrogen market is already valued at over $282 billion/year, growing at 10%/year, rising to 40%/year by 2020, and reaching several trillions of dollars by 2020. In Alberta, Canada, the oil sands need large amounts of hydrogen to convert bitumen to synthetic crude and remove impurities. A key challenge facing the hydrogen economy is a more efficient, sustainable and lower cost method of hydrogen production. As a carbon-based technology, the predominant existing process (steam-methane reforming (SMR) is unsustainable.

Rather than deriving hydrogen from fossil fuels, a promising alternative is the thermochemical decomposition of water. Electrolysis is a proven, commercial technology that separates water into hydrogen and oxygen using electricity. Net electrolysis efficiencies (including both electricity and hydrogen generation) are typically about 24%. In contrast, thermochemical cycles to produce hydrogen promise heat-to-hydrogen efficiencies up to approximately 50%. This article examines the thermophysical properties of a specific cycle called the copper-chlorine (Cu-Cl) cycle, with particular relevance to nuclear-produced hydrogen. A conceptual schematic of the Cu-Cl cycle is shown in Fig. 1.

In the Cu-Cl cycle, water is decomposed into hydrogen and oxygen through intermediate Cu-Cl compounds [4,5]. Nuclear-based "water splitting" requires an intermediate heat exchanger between the nuclear reactor and hydrogen plant, which transfers heat from the reactor coolant to the thermochemical cycle. An intermediate loop prevents exposure to radiation from the reactor coolant in the hydrogen plant, as well as corrosive fluids in the thermochemical cycle entering the nuclear plant.

This paper develops new models for calculating the thermodynamic properties of copper-chlorine compounds in the Cu-Cl cycle. Statistical associating fluid theory is used to calculate the thermodynamic properties, based on the Cotterman equation of state [1-3], as well as the Tang-Lu model [3] from the Ornstein-Zernike equation of state and perturbation chain theory. Predictive models are developed for the calculation of various thermodynamic properties. It extends past the work of Mathias [6] to property evaluation of the specific heat and thermal conductivity. The new predictive models will be used in Aspen Plus simulations of thermochemical processes in the Cu-Cl cycle, particularly to optimize the system configuration, layout and efficiency of hydrogen production.

***Table 1:** Fundamental thermophysical properties for selected Cu-Cl components:*

	HCl	**CuCl**	**$CuCl_2$**
Molecular weight (kg/kmol)	36.4606	98.999	134.451
critical pressure (bars)	82.58 bar[a]	?	?
Critical temperature	51.4 ^0C[a]	?	?
Critical volume	81 cm^3/mol[b]	?	?

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a) NIST Chemistry Web-book, b) Smith, Van Ness Abott, Introduction to Chemical Engineering Thermodynamics

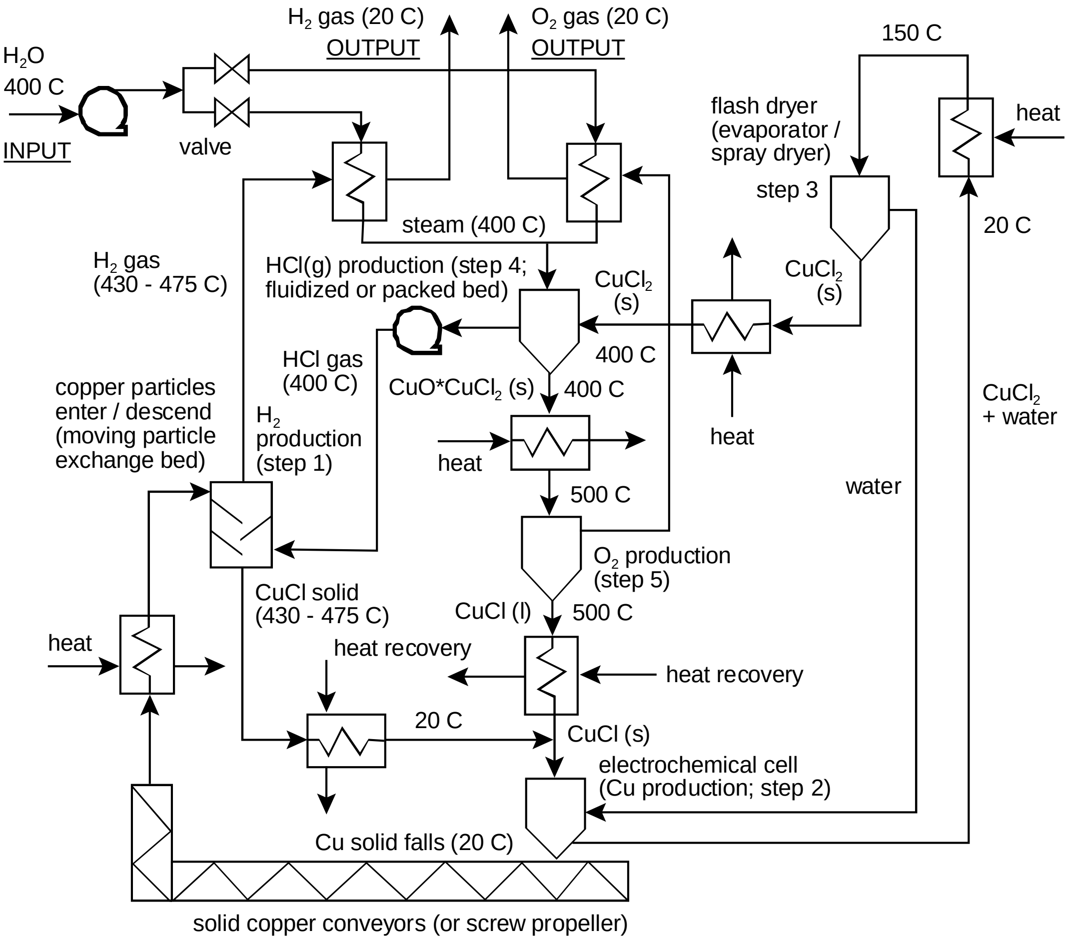

Figure 1: *Schematic of the copper-chlorine cycle for thermochemical hydrogen production [4]*

2 STATISTICAL THERMODYNAMICS FOR FLUIDS

To calculate the thermodynamic functions of state, we will apply the canonical partition [1-2]. Utilizing the semi-classical formulation for the canonical ensemble of the N indistinguishable molecules, the partition function Z can be expressed as follows:

$$Z=\frac{1}{N!h^{Nf}}\int..\int \exp\left(-\frac{H}{kT}\right)\cdot d\vec{r}_1 d\vec{r}_2..d\vec{r}_N d\vec{p}_1 d\vec{p}_2..d\vec{p}_N \qquad (1)$$

where f refers to the number of degrees of freedom of individual molecules, H designates the Hamiltonian molecule system, vectors $\vec{r}_1,\vec{r}_2..\vec{r}_N$.. describe the positions of N molecules and $\vec{p}_1,\vec{p}_2...\vec{p}_N$ momenta, k is Boltzmann`s constant and h is Planck`s constant. The canonical ensemble of the partition function for the system of N molecules can be expressed as:

$$Z = Z_0 Z_{trans} Z_{vib} Z_{rot} Z_{ir} Z_{el} Z_{nuc} Z_{conf} \tag{2}$$

The partition function Z is a product of terms of the ground state (0), translation (trans), vibration (vib), rotation (rot), internal rotation (ir), influence of electron excitation (el), influence of nuclei excitation (nuc) and the influence of the intermolecular potential energy (conf). Utilizing the canonical theory for computing the thermodynamic functions of the state leads to:

Pressure $p = kT\left(\frac{\partial \ln Z}{\partial V}\right)_T$, Internal energy $U = kT^2\left(\frac{\partial \ln Z}{\partial T}\right)_V$,

Free energy $A = -kT \cdot \ln Z$, Entropy $S = k\left[\ln Z + T\left(\frac{\partial \ln Z}{\partial T}\right)_V\right]$, (3)

Free enthalpy $G = -kT\left[\ln Z - V\left(\frac{\partial \ln Z}{\partial T}\right)_V\right]$,

Enthalpy $H = kT\left[T\left(\frac{\partial \ln Z}{\partial T}\right)_V + V\left(\frac{\partial \ln Z}{\partial V}\right)_T\right]$,

where T is temperature and V is the volume of the molecular system.

The various derivatives and expressions of the fundamental equations (3) have an important physical significance. This paper presents expressions which are important with regards to energy exchange processes. The various derivatives below also have a practical significance:

- coefficient of thermal expansion: $\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$ (4)
- isothermal compressibility: $\chi = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T$ (5)
- heat capacity at constant volume per mole: $C_v = \left(\frac{\partial U}{\partial T}\right)_V$ (6)
- heat capacity at constant pressure per mole: $C_p = \left(\frac{\partial H}{\partial T}\right)_p = C_v + \frac{TV\beta^2}{\chi}$ (7)
- velocity of sound: $c_0 = \sqrt{-V^2 \frac{1}{M}\left(\frac{\partial p}{\partial V}\right)_s} = \sqrt{-V^2 \frac{\frac{C_p}{T}\left(\frac{\partial T}{\partial V}\right)_p \frac{1}{M}}{\left(\frac{\partial V}{\partial T}\right)_p - \frac{C_p}{T}\left(\frac{\partial T}{\partial p}\right)_v}}$ (8)

where M is the molecular mass.

For cooling processes, it is also important to calculate the Joule-Thomson coefficient:

$$\mu_J = \frac{1}{C_p}\left(T\left(\frac{\partial V}{\partial T}\right)_{p,\psi} - V\right) \tag{9}$$

Over the past fifty years, accurate models based on statistical thermodynamics have been developed for predicting the thermodynamic properties for simple molecules. By “simple,” we mean molecules for which the most important intermolecular forces are repulsion and dispersion, with weak electrostatic forces due to dipoles, quadrupoles and higher multipole moments. Many hydrocarbons, natural constituents, simple organic and simple inorganic molecules fall within this category. However, many other components such as electrolytes, polar solvents, hydrogen-bonded fluids, polymers, liquid crystals, plasmas and particularly mixtures do not belong to this group. For such fluids, other intermolecular forces become important, such as Coloumbic forces, strong polar forces, complexing forces, effects of association and chain formation, and so forth.

An important type of complex fluid consists of a fluid that associates to form relatively long-lived dimmers or higher n-mers. This type of fluid includes hydrogen bonding, charge transfer and other processes that can occur. The intermolecular forces are stronger than those due to dispersion or weak electrostatic interactions, but still weaker than forces due to chemical bonds.

In recent years, new theories based on statistical thermodynamics have been developed; fluids with chain bonding and association have received much attention because they cover a much wider range of real fluids. A proper theory for these fluids will be very beneficial to chemical engineering applications, by reducing the number of parameters and making them more physically meaningful and predictable. Intermolecular energy exchange processes have vital importance. To calculate the thermodynamic properties of a real Lennard-Jones (LJ) fluid, the **Liu-Li-Lu (LLL)** revised Cotterman equation of state will be applied, based on perturbation theory and the SAFT-VR equation of state for an LJ chain fluid. The newly developed RDF will be applied to the development of a new SAFT model. The model will be used to calculate several typical properties of LJ chains and associating LJ chains. This paper will examine the accuracy of the new models in real engineering practice.

The original derivation of SAFT models can be traced back to work by Wertheim [1-2]. It requires a comprehensive knowledge of graph theory to be fully understood. With the help of the SAFT theory, we can express the residual part of the free energy as follows:

$$A^{res} = A^{seg} + A^{chain} + A^{assoc}$$

For pure components, we can express this with a more-detailed equation, as follows:

$$A^{res} = A^{seg}\left(m\rho, T, \sigma_s, \varepsilon\right) + A^{chain}\left(\rho, d, m\right) + A^{assoc}\left(\rho, T, d, \varepsilon^{AB}, \kappa^{AB}\right) \tag{10}$$

where ρ is the molar density of molecules, m is the number of segments, ε^{AB} is the association energy of interactions between two sites and κ^{AB} is the volume interaction between two sites.

The residual Helmholtz energy consists of three terms representing contributions from different intermolecular forces. The first term A^{seg} represents the segment-segment interactions. In this paper, the segment-segment interactions will be represented by the Lennard-Jones interaction potential. Each segment is characterized by its diameter σ_s and segment interaction parameter ε_s. Each molecule is characterized by the number of segments, m. The second term A^{chain} is the result of the presence of covalent chain-forming bonds between the LJ segments. The third term A^{assoc} is the result of site-site interactions between segments, such as hydrogen bonding. For hydrocarbons, the association term has no importance and it will be ignored in our equations.

The model is developed based on the Liu-Li-Lu model [5], SAFT and perturbation theory associated with a hard sphere, with new coefficients by fitting the reduced pressure and internal energy data from molecular simulations as follows:

$$A^{seg} = A^{hs} + A^{pert} \tag{11}$$

The hard sphere term A^{hs} is calculated with the following expression given by [2]:

$$\frac{A^{hs}}{R_m T} = \frac{6}{\pi\rho}\left[\frac{3\xi_1\xi_2}{1-\xi_3} + \frac{\xi_2{}^3}{\xi_3{}^2(1-\xi_3)^2} + \left(\frac{\xi_2{}^3}{\xi_3{}^2} - \xi_0\right)\ln(1-\xi_3)\right] \tag{12}$$

where the symbol ξ_i is expressed as:

$$\xi_i = \left(\frac{\pi}{6}\right)\rho\sum_i \psi_i m_i d_i{}^i \tag{13}$$

In Eq. (13), d_i represents the hard sphere diameter. It is a temperature-dependent function in terms of ψ_I, which is the molar fraction of component i. In our case, we will use the following equation developed by Cotterman et al.:

$$d_i = \sigma_i \frac{1 + 0.2977T^*}{1 + 0.33163T^* + c_3 T^{*2}} \tag{14}$$

where T^* is the reduced temperature and

$$c_3 = \left(0.0010477 + 0.025337\frac{m_i - 1}{m_i}\right)$$

In the case of a pure fluid, Eq. (12) is reduced to the Carnahan-Starling equation [1-2]:

$$\frac{A^{hs}}{R_m T} = m\frac{4\eta - 3\eta^2}{(1-\eta)^2}\, , \tag{15}$$

For the dispersion term, the following Cotterman equation based on one-dimensional VDW theory for mixtures will be used [1,2]:

$$A^{pert} = m_x \frac{A^{(1)}}{T_x{}^*} + m_x \frac{A^{(2)}}{T_x{}^{*2}} \tag{16}$$

$$\frac{A^{(1)}}{R_m T} = \sum_{m=1}^{4} A_{1m}\left(\frac{\eta}{\tau}\right)^m ,\ \frac{A^{(2)}}{R_m T} = \sum_{m=1}^{4} A_{2m}\left(\frac{\eta}{\tau}\right)^m , \tag{17}$$

$$\tau = 0.7405\ ,\ \ \eta = \frac{\pi\rho d_s{}^3}{6} m_x\ , \tag{18}$$

The effective segment diameter d_s is determined on the basis of Barker perurbation theory. Applying the following developed by Chapman at al. [1,2]:

$$d_s = \sigma_x \frac{1+0.2977T^*}{1+0.33163T^* + c_3 T^{*2}} \tag{19}$$

$$c_3 = 0.0010477 + 0.025337\frac{m_x - 1}{m_x} \tag{20}$$

where

$$T_x^* = \frac{kT}{\varepsilon_x} \tag{21}$$

For mixtures, the following VDW1 mixing rules are used:

$$\begin{aligned} m_x &= \sum_i \psi_i m_i \\ m_x^2 \sigma_x^3 &= \sum_i \sum_j \psi_i \psi_j m_i m_j \sigma_{ij} \\ m_x^2 \varepsilon_x \sigma_x^3 &= \sum_i \sum_j \psi_i \psi_j m_i m_j \varepsilon_{ij} \sigma_{ij} \end{aligned} \tag{22}$$

For the determination of mixing parameters, we use the Lorentz-Berthelot equation:

$$\varepsilon_{ij} = \sqrt{\varepsilon_i \varepsilon_j}, \ \sigma_{ij} = \frac{\sigma_i + \sigma_j}{2} \tag{23}$$

According to Wertheim`s first-order thermodynamic perturbation theory, the contribution to the free energy, due to chain formation of the LJ system, is expressed as follows:

$$\frac{A^{chain}}{NkT} = \sum_i \psi_i (1 - m_i) \ln g^{LJ}(\sigma) \tag{24}$$

Johnson et al.[2] derived a correlation of the radial distribution function for LJ fluids, which is dependent on the reduced temperature and reduced density as follows:

$$g^{LJ}(\sigma_s) = 1 + \sum_{i=1}^{5}\sum_{j=1}^{5} a_{ij} (\rho^*)^i (T^*)^{1-j} \tag{25}$$

In the next section, additional models will be developed for solids and applied to copper-chlorine compounds.

3 STATISTICAL THERMODYNAMICS FOR SOLIDS

In the theoretical formulation for solids, it will be assumed that each form of motion of energy is independent of the others. Thus, the energy of the system of molecules can be written as a sum of the following individual contributions or decoupled forms of motion:

a) vibration energy of molecules (E_{vib}) due to the relative motion of atoms inside the molecules;

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b) potential energy_(E_{pot}) of a system of molecules, which occurs due to the attractive or repulsive intermolecular forces in a system of molecules;
c) energy of electrons (E_{el}), which is concentrated in the electrons or the electron shell of an atom or a molecule;
d) nuclear energy (E_{nuc}), which is concentrated in the atom nucleus.

Define the partition function Z [3], which is applied to the system of particles with a certain volume V, temperature T and particle number N. Assuming that the energy spectrum is continuous, together with the other above assumptions, we can then write the canonical partition function for the one-component system in the following manner [3]:

$$Z = \frac{1}{N!h^{Nf}} \int \ldots \int \exp\left(-\frac{E_{vib} + E_{el} + E_{nuc}}{k_B T} \right) \cdot d\vec{p}_1 \cdot d\vec{p}_2 \ldots . d\vec{p}_N \int \ldots \int \exp\left(-\frac{E_{pot}}{k_B T} \right) d\vec{r}_1 \cdot d\vec{r}_2 .. d\vec{r}_N \tag{26}$$

The second term on the right side of Eq. (9) is called the configurational integral, f is the number of degrees of freedom of an individual molecule, p is momentum, r is the coordinate, and E_{vib}, E_{el}, E_{nuc}, and E_{pot} represent the vibrational energy, electron energy, nuclear energy of individual molecules and potential energy between two molecules, respectively.

Similarly, we can express the partition function Z for a multi-component system of indistinguishable molecules as follows:

$$Z = \frac{1}{\prod_i N_i! h^{N_i f_i}} \int \ldots \int \exp\left(-\frac{E_{vib} + E_{el} + E_{nuc}}{k_B T} \right) d\vec{p}_1 \cdot d\vec{p}_2 \ldots d\vec{p}_N \cdot \int .. \int \exp\left(-\frac{E_{pot}}{k_B T} \right) d\vec{r}_1 \cdot d\vec{r}_2 \ldots d\vec{r}_N \tag{27}$$

In Eq. (2) N_i is the number of molecules of the i-th component, and f_i is the number of degrees of freedom of the i-th molecule. Using the canonical partition, the partition function Z of the one-component system as a product of partition functions becomes:

$$Z = Z_0 Z_{vib} Z_{el} Z_{nuc} Z_{conf} \tag{28}$$

For a system of many components, the partition function Z can be written as a product of partition functions for individual terms:

$$Z = \prod_i (Z_0 \cdot Z_{vib} \cdot Z_{el} \cdot Z_{nuc})_i Z_{conf} = \prod_i Z_i Z_{conf} \tag{29}$$

3.1 Vibration properties of solids

Our thermodynamic system consists of N particles associated by attractive forces. Atoms in a crystal lattice are not motionless, as they oscillate in their positions of equilibrium. At temperatures below the melting point, the motion of atoms is approximately harmonic, [2]. This assembly of atoms has 3N-6 vibration degrees of freedom. We will neglect 6 vibration degrees of freedom and mark the number of vibration degrees of freedom with 3N.

Through the knowledge of independent harmonic oscillators, the distribution function Z [3] can be derived as follows:

$$Z=\left[\frac{\exp\left(-\frac{h\nu}{2k_BT}\right)}{1-\exp\left(-\frac{h\nu}{k_BT}\right)}\right]^{3N} \tag{30}$$

where ν is the oscillation frequency of the crystal. The term hν/k is the Einstein temperature.

When comparing the experimental data for simple crystals, a relatively good match with analytical calculations at higher temperatures is observed, whereas at lower temperatures the discrepancies are higher. This explains why Debye corrected Einstein's model by taking account of the interactions between a numbers of quantized oscillators. The Debye approximation treats a solid as an isotropic elastic substance. Using the canonical distribution, the partition function may be written as:

$$\ln Z=-\frac{9}{8}N\frac{\theta_D}{T}-3N\cdot\ln\left(1-\exp\left(-\frac{\theta_D}{T}\right)\right)+3N\frac{T^3}{\theta_D{}^3}\int_0^{\theta_D/T}\frac{\xi^3}{\exp(\xi)-1}d\xi \tag{31}$$

In Eq. (31), θ_D is the Debye temperature. By expanding the third term in equation (31) into a series for a higher temperature range,

$$\frac{\xi^3}{\exp(\xi)-1}=\xi^2-\frac{1}{2}\xi^3+\frac{1}{12}\xi^4-\frac{1}{720}\xi^6+...... \tag{32}$$

Using Eqs. (31) and (32) leads to the following expression:

$$\begin{aligned}\ln Z=&-\frac{9}{8}N\frac{\theta_D}{T}-3N\cdot\ln\left(1-\exp\left(-\frac{\theta_D}{T}\right)\right)+\\&3N\left(\frac{T}{\theta_D}\right)^3\left[\begin{matrix}\frac{1}{3}\left(\frac{\theta_D}{T}\right)^3-\frac{1}{8}\left(\frac{\theta_D}{T}\right)^4+\frac{1}{60}\left(\frac{\theta_D}{T}\right)^5\\-\frac{1}{5040}\left(\frac{\theta_D}{T}\right)^7+\frac{1}{272160}\left(\frac{\theta_D}{T}\right)^9-..\end{matrix}\right]\end{aligned} \tag{33}$$

The relation between the Einstein and Debye temperature may be written as:

$$\theta_E=0.735\theta_D$$

The Debye characteristic temperature was determined by means of the Grüneisen independent constant γ:

$$\theta_D=CV^{-\gamma}\,, \tag{34}$$

where C is a constant, dependent on the material. This mathematical model can be used for the calculation of thermodynamic properties of polyatomic crystals. The derivations of the Einstein and Debye equations, outlined previously, apply specifically to monoatomic solids, i.e. those belonging to the cubic system. However, experiments have shown that the Debye equation also predicts the values of specific heat and other thermophysical properties for certain other monoatomic solids, such as zinc, which crystallizes in the hexagonal system.

Consider that the crystal contains N molecules, each composed of s atoms. Since there are N·s atoms, the crystal as a whole has 3·N·s vibrational modes. A reasonable approximation is obtained by classifying the vibrations as follows:

- 3N lattice vibrations, which are the normal modes in the Debye model (acoustical modes);
- independent vibrations of individual molecules, in which bond angles and lengths may vary (there must be 3·n(s-1) of these optical modes, which were expressed by the Einstein model).

3.2 Crystal bonds

The analytical calculation of the configuration integral in solids is a difficult task. The most frequently used numerical procedures are applied in practical computations by means of the Monte-Carlo method. The current method requires much computer time, with a serious drawback that it does not provide a functional dependence of thermodynamic properties on temperature and volume. Empirical equations are frequently used, although mostly without any theoretical basis, built on a molecular view. In this paper, a perturbation VDW theory is used for solids, based on the model of hard spheres, to calculate the thermodynamic properties of state. In order to calculate the mixtures of atoms of hard spheres, we obtain the following configuration-free energy for a certain binary crystal:

$$A_{conf0} = Nk_BTx\begin{pmatrix} -3\ln\left(\frac{V^*-1}{V^*}\right) + 5.124\cdot\ln V^* - 20.78V^* + 9.52V^{*2} - 1.98V^{*3} \\ + C_0 + \psi_1\cdot\ln\psi_1 + \psi_2\cdot\ln\psi_2 \end{pmatrix} \tag{35}$$

$$C_0 = 15.022, \qquad V^* = \frac{V}{V_0} \qquad V_0 = \frac{N\sigma^3}{\sqrt{2}} \tag{36}$$

where σ is the Lennard-Jones parameter, V^* is the reduced volume and ψ_1 is a molar fraction of component 1. In the case of a crystal formed of atoms of the same type, the free energy can be written as:

$$A_{conf0} = Nk_BT\left(-3\ln\left(\frac{V^*-1}{V^*}\right) + 5.124\cdot\ln V^* - 20.78V^* + 9.52V^{*2} - 1.98V^{*3} + C_0\right) \tag{37}$$

To calculate the perturbation contribution, the VDW model was used. In previous literature [3] the VDW model is treated in relation to the atomic structure, whereas we additionally present the temperature-dependent coefficients below.

$$A_{conf1} = -\frac{a(\psi_1,\psi_2,T)}{V} \tag{38}$$

The configuration integral is thus formed by the contribution of hard spheres and a perturbation:

$$A_{conf} = A_{conf0} + A_{conf1} \tag{39}$$

In our case, the coefficient is determined as a temperature-dependent polynomial, based on a comparison between experimental data and analytical results:

$$a = a_0 + a_1 T + a_2 T^2 \tag{40}$$

The coefficients a_0, a_1, a_2 are obtained by numerical approximation and comparisons with thermodynamic data.

3.3 Bulk and elastic modulus

Using Eq. (16), the derived thermodynamic properties of state are determined. The isobaric heat capacity is important for the calculation of parameters such as the thermal diffusivity of solids:

$$C_p = \left(\frac{\partial H}{\partial T}\right)_p \tag{41}$$

The bulk modulus relates the relative pressure change and the applied stress.
Isentropic bulk modulus:

$$K_S = -V\left(\frac{\partial p}{\partial V}\right)_S \tag{42}$$

Isothermal bulk modulus:

$$K_T = -V\left(\frac{\partial p}{\partial V}\right)_T \tag{43}$$

The modulus of elasticity, E, is also known as Young's modulus and it is the measure of the elastic force of any substance, expressed by the ratio of a stress on a given unit of the substance to the accompanying distortion. For highly symmetric solids, Young's modulus can be written in terms of the bulk modulus and Poisson ratio as follows,

$$E = 3K(1 - 2\nu) \tag{44}$$

The volumetric expansion coefficient β is: $\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_{P,\psi}$ (45)

For many engineering applications, a quantity of direct interest is not only the coefficient of volume expansion β, but rather the coefficient of linear expansion α:

$$\alpha = \frac{1}{V^{1/3}}\left(\frac{\partial V^{1/3}}{\partial T}\right)_p = \frac{1}{3}\beta \tag{46}$$

3.4 Murnaghan equation of state for solids

The internal energy of a solid, u, can be expressed as the sum of the following two terms:

$$u_T(v,T) = u_0(v) + u_D(T,v) \tag{47}$$

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where u_0 represents the cohesive energy at zero temperature. On the basis of relations from classical thermodynamics, ($-p = \left.\frac{\partial u_t}{\partial v}\right|_S$), $p = p_0 + u_D \frac{\gamma}{V}$ (48)

Using constants explained in Ref. [2], the pressure at zero temperature p_0 can be expressed by

$$p_0 = B_0 \frac{3\left[\left(\frac{V}{V_0}\right)^{1/3} - 1\right]}{\left(\frac{V}{V_0}\right)^{2/3}} e^{-\alpha}\left(1 - 0.15\alpha + 0.05\alpha^2\right) \tag{49}$$

4 RESULTS AND DISCUSSION

In this section, the results of the thermodynamic property evaluations will be performed over a range of temperatures. In Figs. 2-4, the thermodynamic properties of HCl are determined based on statistical thermodynamic formulations presented in the previous section. Then the properties of solid copper are shown in Figs. 5-7, including the thermal expansion coefficient, isothermal bulk modulus and modulus of elasticity. It can be observed that the thermal expansion coefficient increases with temperature, while the bulk modulus and modulus of elasticity show opposite trends. Relatively close agreement between predicted and measured data are shown in the figures. Based on the three forms of CuCl identified by Mathias [5], a step change in predicted enthalpy can be observed in Fig. 8. All three forms of CuCl were studied to determine the thermodynamically preferred form. In Fig. 9, the predicted enthalpy of CuCl in the liquid and gas regions is shown. A step change is observed at the phase transition point. Additional results of entropy at varying temperatures are shown in Fig. 10. In the previous results, the calculations of thermodynamic properties for solids are determined based on the following Shomate equation:

$$C_p = A + BT + CT^2 + DT^3 + \frac{E}{T^2} \tag{50}$$

$$H = \int C_p dT, \quad S = \int C_p \frac{dT}{T} \tag{51}$$

Previous studies [5] have shown that CuCl exists in two crystalline forms: a cubic form up to 412 °C and a beta-hexagonal form above this temperature. The melting point of CuCl is 423 °C, so the temperature range of the beta-hexagonal form is small. CuCl may have one of the following three preferred forms at any given temperature: CuCl (liquid), CuCl(SC) (cubic) and CuCl(SB) (beta-hexagonal). It is known that the enthalpy and the Gibbs energy of formation of CuCl(SC) at 25 °C are -137.0 kJ/mol and -120.0 kJ/mol, respectively. The enthalpy change for transition between the cubic and beta-hexagonal forms at 412 °C is 6.0 kJ/mol. Also, the enthalpy of fusion for transition from the beta-hexagonal solid to the melt at 423 °C is 7.08 kJ/mol. Using these properties, thermodynamic correlations for the three forms of CuCl can be developed [2-6] and the results are shown in Figs. 8-9. The values of Gibbs free energy and enthalpy of the cubic form at 25 °C are -120 and -137 kJ/mol, respectively, since this is the stable form, at that temperature. The values G and H of the other two forms at 25 °C are set to obtain the correct enthalpy of transition and continuity in value of G. The standard-state values of G and H of the beta-hexagonal form can be obtained from the value of 6.5 kJ/mol for the enthalpy of transition from the cubic form at 412 °C.

Classical thermodynamics calculates the thermodynamic properties of matter on the basis of macroscopic observation of processes in the physical world. The calculation of thermodynamic properties of state is extremely important for industrial processes, such as processing plants, cooling plants, combustion processes, etc. There are many semi-empirical formulations (Van der Waals, Peng-Robinson, Redlich-Kwong, Soave, etc.). Their advantage is mathematical simplicity. However, equations are less accurate in the region of higher pressures. Numerous complex semi-empirical equations also exist for the calculation of thermodynamic properties of state (Benedict-Webb-Rubin (BWR), Lee-Kesler, Benedict-Webb-Rubin-Starling (BWRS) and so on) [5]. The main drawback of semi-empirical equations is their limited use within prescribed pressure and temperature limits. They also provide no direct insight into the microstructure of matter. Similarly, the calculation of the second virial coefficient, which takes into account the influence of the intermolecular potential on the interaction of molecules between the pairs of particles, does not provide sufficiently accurate forecasts when using semi-empirical equations. Most of these formulations can be derived theoretically, under the assumption of a rough influence of intermolecular attractive and repulsive forces.

Thermal and caloric equations of state for solids are fundamental characteristics of matter defining thermodynamic properties over a wide range of temperatures. The major problem of the current theories is the necessity off correctly taking into account the collective and inter-particle interactions of disordered media. Solids have been extensively studied based on classical thermomechanics. These models arise from a practical view and they allow simulation over a wider temperature and pressure range, but classical thermomechanics gives little or no insight into the microstructure of the substance. However, it allows the calculation of thermodynamic functions of state with assistance from measurement or empirical equations. Statistical thermodynamics, in contrast, has been used in the current results. It calculates the properties of state on the basis of molecular motions in space and corresponding intermolecular interactions. This paper is one of the first attempts (to our knowledge) to determine how to calculate vibrational properties for Cu-Cl compounds on the basis of statistical thermodynamics, with analytical vibrational theory.

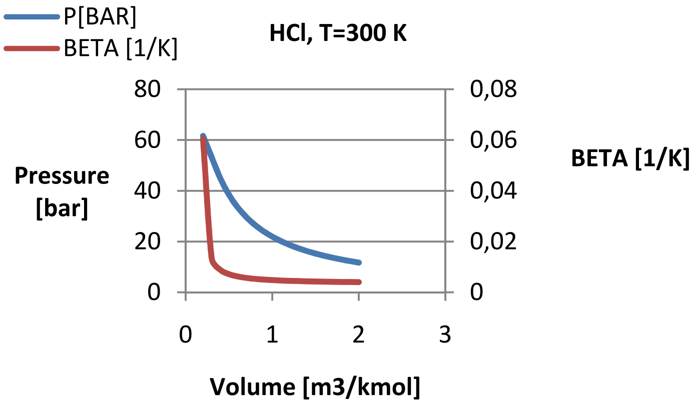
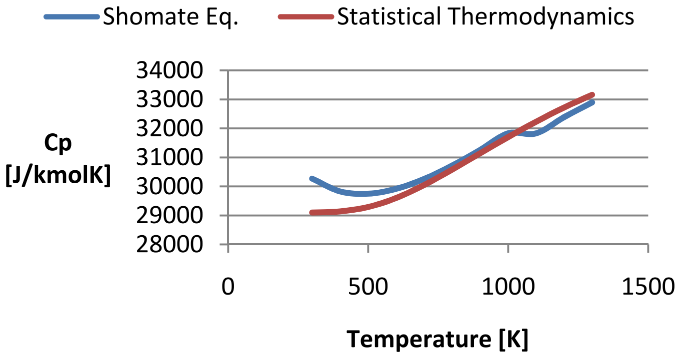


Figure 2: *Thermodynamic properties of HCl obtained by statistical thermodynamics*



Figures 3: *Thermodynamic properties of HCl obtained by statistical thermodynamics*

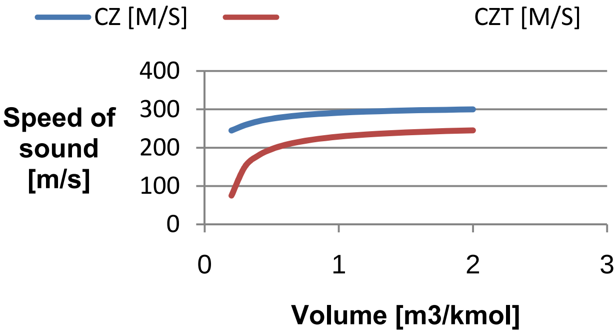


Figure 4: *Thermodynamic properties of HCl obtained by statistical thermodynamics*

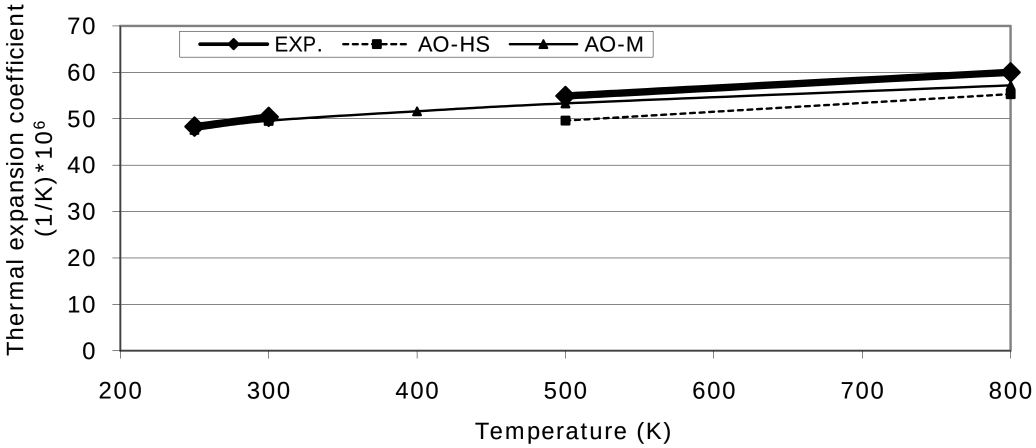


Figure 5: *Thermal expansion coefficient for copper*

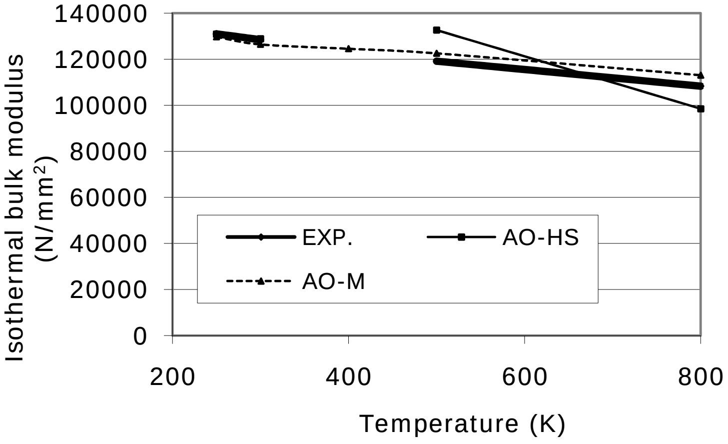


Figure 6: Isothermal bulk modulus for copper

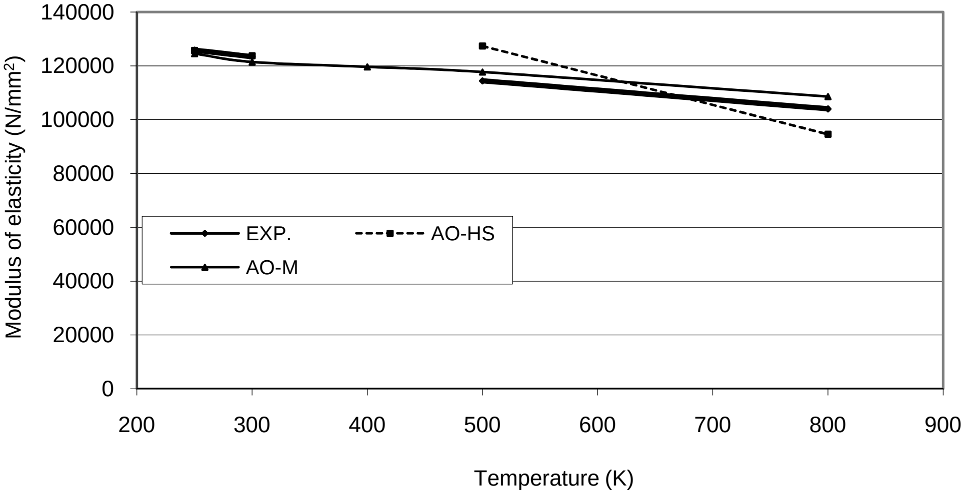


Figure 7: Modulus of elasticity for copper

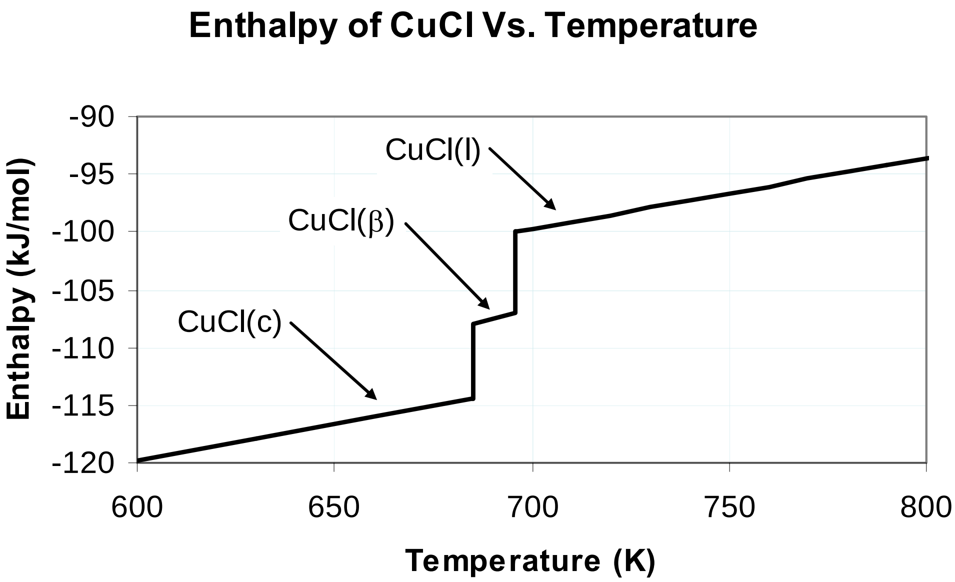


Figure 8: *Enthalpy of CuCl at varying temperatures*

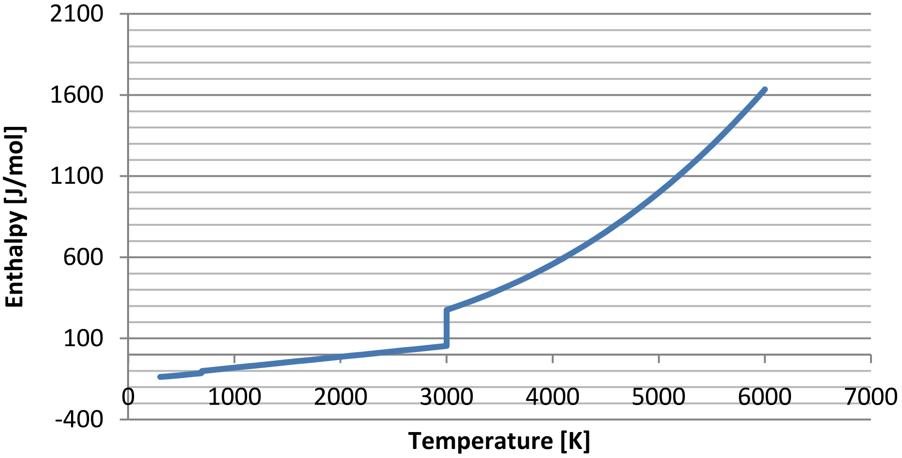


Figure 9: *Enthalpy of CuCl (based on Shomate's equation)*

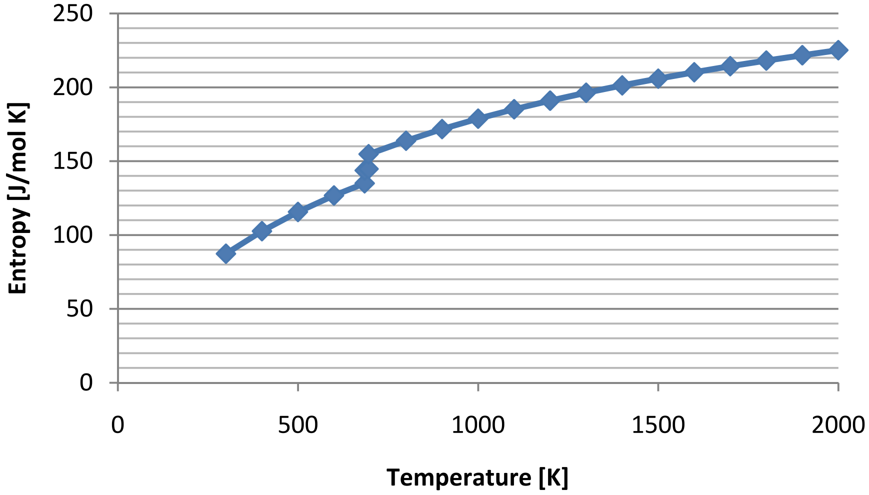


Figure 10: *Entropy of CuCl (based on Shomate's equation)*

5 CONCLUSIONS

This paper has examined the thermodynamic property evaluation of copper-chlorine mixtures (particularly cupric chloride) at high temperatures. These compounds have importance in a Cu-Cl thermochemical cycle for hydrogen production. Cupric chloride undergoes solid-solid and solid-liquid phase changes in the selected range of operating temperatures, which leads to corresponding step changes of thermodynamic properties at the phase transition. Analytical models have been developed based on statistical thermodynamics and chain theory to determine thermophysical properties of CuCl and HCl in both liquid and gas regions.

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INVESTMENTS IN RENEWABLE ENERGY SOURCES AND CASES OF GOOD PRACTICES OF FISCAL STIMULATION IN THE EU

INVESTICIJE V OBNOVLJIVE ENEREGTSKE VIRE IN PRIMERI DOBRE PRAKSE FISKALNIH SPODBUD V EU

Mejra Festić [ℜ]

Key words: fiscal stimulation, renewable energy sources, investment.

Abstract

According to the fulfilment of economic criteria of technologies on renewable energy sources and their contribution to the macro-economic environment, there is a need for the establishment of an adequate system of fiscal stimulations. The criteria for such a system of fiscal stimulations of investment in technologies on renewable energy sources is the price of electricity produced by a specific technology with renewable sources. Therefore, we can state the implications for energetic policy: approch of lowering the capital costs, stimulations schemes that are adopted to the life-cycle of the technology and technical efficiency; and a combination of instruments that are related to supply and demand for electricity energy obtained from renewable sources.

Povzetek

Glede na ekonomičnost in prispevek posameznih tehnologij OVE k narodnogospodarskim makro kazalnikom je treba oblikovati tudi ustrezen sistem stimuliranje države k OVE investicijam v energetiki. Kriterij davčnih spodbud in olajšav za investicije OVE naj bi bila lastna cena električne

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[ℜ] 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.

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energije posameznih OVE tehnologij. Zato bi lahko strnili kot implikacije za energetsko politiko: zniževanje stroškov kapitala, stimulacijskih shem, ki ustrezajo tehnično pogojeni učinkovitosti in življenjski dobi OVE energetskih objektov; in kombinaciji instrumentov, ki se nanašajo tako na proizvodnjo kot povpraševanje po električni energiji iz OVE.

1 INTRODUCTION TO THE FISCAL LEGISLATION AND THE POLICY REGARDING INVESTMENTS IN NEW ENERGY-GENERATING FACILITIES AND IN NEW TECHNOLOGIES

Introduction. Slovenia is obliged to achieve its target share of the electric power generation from alternative renewable sources, also involving the need and demand for fiscal and tax incentives for investments into the energy generation facilities generating electric power from alternative sources. The reference member states relevant for Slovenia are Italy, Austria, Germany, Denmark, the Netherlands, and the Scandinavian countries. Considering the climatic conditions, the potentials of the utilisation of alternative energy sources in Slovenia are quite specific. For this reason, the above-cited states are the most comparable to Slovenia.

The complexity of the institutional conditions, the macro-economic environment, the GDP structure, and the climatic conditions are the factors providing the basis for the assessment of the economic viability of investments in alternative sources, respectively, into the energy- generating facilities, based on renewable energy sources (RES).

Environmental issues dictate the necessity of development and sophistication of renewable sources, such as solar energy, biomass energy, geothermal energy, hydro energy, wind energy, and heat pump energy. The support policies in the EU and in Slovenia foster RES development, primarily hydroelectric power plants. Directive EC/2001/77 obliges Slovenia to generate at least 33.6 % of its electric power from renewable sources by year 2010, as well as attaining a share of 12 % of its total energy from renewable sources. The requirement for the certification of the energy source, the Kyoto protocol, requirements for better energy efficiency, the determination of the share of RES in public buildings, as well as the system of public tenders for the RES-based new electric power plants, dictate the need for the standardization of the integration of micro- and small electric power plants into the system, as well as the need for the assurance of the medium-term stability of the electric power buying-in prices from the RES-based electric power plants, and the provision of tariff consumers with the possibility of the free purchase of electric power from the qualified producers with the minimum network costs. Slovenia encounters an inadequate global approach, intensifying difficulties in the decision-making process and the implementation of such investments, since such an approach requires the involvement of environmental organizations, as well as the initiatives of action groups and local communities. If a unified, positive, and active position was adopted with regard to renewable energy sources, reducing negative impacts on environment, the potential provided by the technological progress could enable a realization of a bigger yield. A fully integrated approach is required in order to ensure sustainable energy services, considering that the intensity of energy development in Slovenia lags behind its potential, which is provided by the eco-system and climatic efficiencies.

The financing is relatively simpler, considering the minor capital intensity and minor value of investments into RES. Initial costs are higher, while the repayment period is longer, and for this reason, the banks very often do not support the projects of the kind, the revenues in the initial periods being too small. The non-refundable means of the Agency for the Efficient use and RES are also available for this purpose (within the framework of the budget funds), as well as the favourable loans of the Environmental Protection Development Fund of Slovenia, operating as a specialized financial organization for financing the environmental requirements; tax allowances and the EU funds should be mentioned as well. The inhabitants of local communities in Denmark and Germany frequently support the construction of minor RES-based electric power plants, thus ensuring for themselves the *energy independence and a foreseeable energy price.*

The merits of renewable sources lie in the *lowering of the import dependency* from imported energy sources and in the *rise of the energy security*, *in encouraging employment and development of enterprises.* The RES industry (one of the newest and most dynamic sectors) and RES technology are more labour intensive per product unit when compared with the technology of fossil fuels utilisation, which would lead to an increase in the added value of the region. Further merits are the *upgrading environment quality* and the *prevention of further climatic changes* (RES significantly reduce the emissions of CO_2 and consequently facilitate compliance with the Kyoto protocol criteria, such investments being ecologically acceptable), as well as the *increase of the opportunities of better harmonization of energy types with local requirements* (such investments result in a higher employment rate in the region and lower energy dependency). Investments of this kind can also be used *for the renovation of obsolete technology* of energy generation (power plants can be renovated to be more efficient) and consequently the *energy efficiency of the region can be intensified* (to achieve this objective, the responsibility for the implementation of investments in the minor renewable energy-generating facilities should be delegated to local communities).

Experiences of other states and best practice examples. The initiatives to invest into renewable energy sources differ from one EU country to another with regard to the specific features of their sources and costs of their utilisation. Considering the costs of the choice of renewable sources (wind energy, wood biomass, biofuel, small hydro-electric plants, and photovoltaics), the fiscal incentives and tax allowances differ, too. The choice of institutional incentives depends also on the energy efficiency of the RES.[1]

The costs of wind-generated electric power differ among EU member states and therefore the amounts of incentives also differ (from €30/MWh in Slovakia up to €110/MWh in Great Britain). Denmark, Germany, and Spain are the member states that use the wind energy most efficiently (see Table 1). Maintenance tariffs have been most frequently used instrument. Experience also demonstrates the conditionality of the sufficiency of incentives upon the period of duration of the tariffs. The subsidies per MWh, however, are conditional upon the costs of electric power generation per MWh, and exceed, predominately, the cost item (in Belgium, France, Germany, Spain, Italy, Portugal, and in Great Britain). Germany even provides soft loans to those investing in the wind energy-generating facilities. Finland encourages electric power generation from biomass. However, in Slovakia, Slovenia, Latvia, and Estonia a comparison of cost and subsidies per MWh for the wind energy demonstrates a setback of subsidies when compared to the marginal costs of the wind-generated electric power. Unlike the afore-mentioned new member states, the incentives in the Czech Republic, in Lithuania, and in Hungary are adequate.

The promotion of biofuel is insufficient in Sweden and in France and depends on the marginal costs. Incentives in Greece, Ireland and Portugal are relatively good; they are better in Germany

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[1] The energy efficiency of the RES is the ratio between the change of the potential of the electric power generation from the RES within a certain period and the additional medium-term feasible potential by year 2020.

and Austria, moderate in Denmark, and very high in Great Britain. The significance of biofuel in Italy and Great Britain has strengthened on the account of the enlargement of land meant for this purpose. Larger facilities generating energy from biofuel are more efficient than smaller ones. The utilisation of biofuel is stimulated by means of secondary instruments (tax exemptions and tax allowances). The maintenance schemes and green certificates are also frequently used. New member states have low subsidies regarding the marginal costs of the MWh generation. With the exception of Slovenia and the Czech Republic, incentives are insufficient in all other member states.[2]

An insignificant share of the biomass potential was used in EU-15 in the period from 1998 to 2003. When compared with the wind energy efficiency, the efficiency of this potential is also lower. The efficiency indicator of the biomass yield in Denmark, Finland, and in Belgium is relatively favourable in comparison to the other states (Table 1). Denmark has considerably increased the utilisation of its biomass potential since 2001; likewise, since 2003, a rise has been noticed in the Netherlands. Finland and Sweden encouraged the increase in utilisation of biomass by tax allowances and subsidies. The encouraging of biomass in Austria and in Germany is a part of the policy in the rural, development, and energy domain (also evident from a favourable subsidy/cost ratio). The disparity between subsidies and costs is less noticeable in Denmark, in the Netherlands and in Finland, also indicating a higher efficiency of biomass utilisation. Incentives in Great Britain, Belgium and Italy are sufficient; however, the yield is relatively poor when compared with that in the leading states in this field. Nevertheless, incentives in other states are not sufficient to achieve higher significance and a greater share of the alternative biomass source.

The exploitation of small hydroelectrical energy facilities demonstrates considerable differences in the costs of the electric power generation from this source per member states. In most cases, the subsidies are adjusted to the generation costs, and only in Belgium, Austria, Finland, Cyprus, Latvia, and Slovakia, do the subsidies fall short of costs. However, the efficiency of small hydroelectric plants was the highest in Spain, Belgium, Germany, Greece and Italy.

Photovoltaic solar energy is most strongly present in Germany, the Netherlands and Austria. Incentives in these member states are complex and include maintenance tariffs, soft loans, mandatory quotas, tax allowances and exemptions, as well as subsidies. The instruments are integrated into the development and environmental policy.

Table 1: *Allocation of member states as per investment incentive instruments in RES*

Maintenance tariffs	Germany, Denmark, France, Portugal, Luxembourg, Greece, Spain, the Netherlands, Austria
System of certificates	The Netherlands, Austria, Sweden, Italy, Belgium, Great Britain
Public tenders	Ireland
Tax incentives	Great Britain, Finland, the Netherlands
Mandatory quotas	Belgium, Sweden, Great Britain, Italy

Source: Euroelectric (2004).

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[2] The utilisation of biofuel often reduces the cultivable areas for food, which results in the reduction of environmental advantages.

Table 2: *Incentives for investments in RES by member states and by sources (for a period of 15 to 20 years)*

	Wind energy (average subsidy/ minimum to average generation costs) in €/MWh	Wind energy efficiency (maintenance tariffs/ mandatory quotas/ public tenders/fiscal incentives and subsidies[1]	Biofuel (average subsidy/ minimum to average generation costs) in €/MWh[2]	Biofuel energy efficiency (maintenance tariffs/ mandatory quotas/ public tenders/ fiscal incentives and subsidies)	Wood biomass (average subsidy/ minimum to average generation costs) in €/MWh	Biomass energy efficiency (maintenance tariffs/ mandatory quotas/ public tenders/fiscal incentives and subsidies)	Small hydroelectric plants (average subsidy/ minimum to average generation costs) in €/MWh	Small hydroelectric plants energy efficiency (maintenance tariffs/ mandatory quotas/ public tenders/fiscal incentives and subsidies)	Photovoltaics (average subsidy/ minimum to average generation costs) in €/MWh	Photovoltaic efficiency (maintenance tariffs/ mandatory quotas/public tenders/fiscal incentives and subsidies)
Austria	€78/MWh €60-80 /MWh	3.7 % (maintenance tariffs)	€122/MWh €60-110 /MWh	0.7 % (maintenance tariffs)	€108/MWh €40-80 /MWh	0.1 % (maintenance tariffs)	€49/MWh €57-83 /MWh	0.75 % (maintenance tariffs)	€500/MWh €610-810 /MWh	1 % (maintenance tariffs)
Belgium	€98/MWh €58-78 /MWh	0.4 % (maintenance tariffs and mandatory quotas)	€83/MWh €60-90 /MWh	0.65 % (maintenance tariffs and mandatory quotas)	€84/MWh €35-70 /MWh	1.1 % (maintenance tariffs and mandatory quotas)	€98/MWh €110-140 /MWh	4% (maintenance tariffs and mandatory quotas)	€480/MWh €740-1000 /MWh	0.01 % (maintenance tariffs)
Denmark	€53/MWh €48-60 /MWh	9.4 % (maintenance tariffs)	€82/MWh €60-90 /MWh	1.4 % (maintenance tariffs)	€73/MWh €76-81 /MWh	4% (maintenance tariffs)	-	0%	€40/MWh €780-980 /MWh	0.02 % (maintenance tariffs)
Finland	€48/MWh €58-75 /MWh	0.2 % (fiscal incentives and subsidies)	€58/MWh €60-103 /MWh	0.2 % (fiscal incentives and subsidies)	€58/MWh €74-78 /MWh	4.5% (fiscal incentives and subsidies)	€40/MWh €60-70 /MWh	0.6 % (fiscal incentives and subsidies)	€35/MWh €810-1100 /MWh	-
France	€79/MWh €53-64 /MWh	0.2 % (public tenders and maintenance tariffs)	€59/MWh €60-100 /MWh	0.3% (public tenders and maintenance tariffs)	€57/MWh €59-69 /MWh	-0.2 % (public tenders and maintenance tariffs)	€64/MWh €40-63 /MWh	0.95% (public tenders and maintenance tariffs)	€180/MWh €620-820 /MWh	0.015% (maintenance tariffs and public tenders)

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[3] Applicable for the period 1998 to 2004.
[4] Applicable for the period 1998 to 2003.

Germany	€81/MWh €58-84 /MWh	8.3 % (maintenance tariffs)	€93/MWh €60-100 /MWh	2.9% (maintenance tariffs)	€110/MWh €62-67 /MWh	0.4 % (maintenance tariffs)	€90/MWh €80-100 /MWh	3% (maintenance tariffs)	€580/MWh €680-950 /MWh	1.85 % (maintenance tariffs)
Greece	€71/MWh €57-77 /MWh	1.8 % (maintenance tariffs)	€63/MWh €60-110 /MWh	1.1 % (maintenance tariffs)	€68/MWh €62-78 /MWh	-	€63 /MWh €50-80 /MWh	3.5 % (maintenance tariffs)	250 €/MWh 500-680 €/MWh	0.01 % (maintenance tariffs)
Ireland	€57/MWh €52-58 /MWh	2.2 % (public tenders)	€62/MWh €60-100 /MWh	-0.05 % (public tenders)	€62/MWh €90-98 /MWh	-	€79/MWh €58-100 /MWh	0%	€38/MWh €750-950 /MWh	-
Italy	€96/MWh €58-77 /MWh	1.1 % (maintenance tariffs and mandatory quotas)	€96/MWh €60-100 /MWh	1.15% (maintenance tariffs and mandatory quotas)	€95/MWh €40-78 /MWh	0.2 % (maintenance tariffs and mandatory quotas)	€90 /MWh €50-70 /MWh	2.2 % (maintenance tariffs and mandatory quotas)	€590/MWh €580-780 /MWh	0.015 % (maintenance tariffs and mandatory quotas)
Luxembourg	€79/MWh €60-82 /MWh	6.8 % (maintenance tariffs)	€70/MWh €60-105 /MWh	1.9 % (maintenance tariffs)	€70/MWh €80-82 /MWh	-	€70 /MWh -	0%	€580/MWh €750-1000 /MWh	3 % (maintenance tariffs)
The Netherlands	€69/MWh €57-79 /MWh	4.4 % (maintenance tariffs and mandatory quotas)	€72/MWh €60-85 /MWh	0.3 % (maintenance tariffs and mandatory quotas)	€71/MWh €40-70 /MWh	4.3 % (maintenance tariffs and mandatory quotas)	€80/MWh -	0%	€90/MWh €750-1000 /MWh	0.4 % (maintenance tariffs and mandatory quotas)
Portugal	€67/MWh €58-76 /MWh	2.1 % (maintenance tariffs)	€73/MWh €60-110 /MWh	0.0% (-)	€74/MWh €68-73 /MWh	0.65 % (maintenance tariffs)	€73/MWh €70-100 /MWh	1% (maintenance tariffs)	€380/MWh €420-590 /MWh	-
Spain	€78/MWh €52-73 /MWh	8.3 % (maintenance tariffs)	€74/MWh €60-100 /MWh	0.4 % (maintenance tariffs)	€74/MWh €60-73 /MWh	1.8 % (maintenance tariffs)	€80/MWh €50-63 /MWh	20.5 % (maintenance tariffs)	€400/MWh €430-600 /MWh	0.08 % (maintenance tariffs)
Sweden	€64/MWh €48-71 /MWh	0.9 % (fiscal incentives)	€58/MWh €60-100 /MWh	0.2 % (fiscal incentives)	€52/MWh €62-75 /MWh	1.2 % (fiscal incentives)	€49/MWh €40-50 /MWh	0.45 % (fiscal incentives)	€40/MWh €820-1020 /MWh	-
Great Britain	€110 /MWh €58-62 /MWh	0.7 % (maintenance tariffs and public tenders)	€110/MWh €60-100 /MWh	2.9 % (public tenders and maintenance tariffs)	€80/MWh €38-64 /MWh	1.2 % (public tenders and maintenance tariffs)	€115/MWh €80-118 /MWh	1.5 % (public tenders and maintenance tariffs)	€380/MWh €750-1000 /MWh	0.01 % (maintenance tariffs and public tenders)

Cyprus	€83/MWh €55-60 /MWh	0.3 % (maintenance tariffs)	€63/MWh €60-118 /MWh	0% (-)	€62/MWh €100-110 /MWh	0.0%	€62/MWh €64-100 /MWh	0%	-	-
Check Republic	€88/MWh €58-64 /MWh	0.1 % (maintenance tariffs)	€77/MWh €60-105 /MWh	-0.3 % (maintenance tariffs and mandatory quotas)	€70/MWh €10-75 /MWh	-0.02%	€45/MWh €43-85 /MWh	3.6 % (maintenance tariffs and mandatory quotas)	-	-
Estonia	€51/MWh €51-58 /MWh	0.5 % (maintenance tariffs)	€50/MWh €60-108 /MWh	0.3 % (maintenance tariffs)	€50/MWh €10-90 /MWh	0.05 % (maintenance tariffs)	€50/MWh €25-30 /MWh	10.4 % (maintenance tariffs)	-	-
Hungary	€66/MWh €60-68 /MWh	0.1 % (maintenance tariffs)	€64/MWh €60-102 /MWh	0.2 % (maintenance tariffs)	€64/MWh €18-100 /MWh	0.25 % (maintenance tariffs)	€63/MWh €50-95 /MWh	1.2 % (maintenance tariffs)	-	-
Latvia	€55/MWh €57-62 /MWh	0.6 % (maintenance tariffs, mandatory quotas)	€49 /MWh €60-100 /MWh	0.6 % (maintenance tariffs and mandatory quotas)	€50/MWh €96-100 /MWh	0.02 % (fiscal incentives and subsidies)	€50/MWh €60-80 /MWh	4.85 % (maintenance tariffs and mandatory quotas)	-	-
Lithuania	€64/MWh €58-63 /MWh	0.0% (-)	€60/MWh €60-100 /MWh	0.05 % (maintenance tariffs)	€55/MWh €90-100 /MWh	0.02 % (maintenance tariffs)	€58/MWh €55-70 /MWh	4.1 % (maintenance tariffs)	-	-
Malta	€0/MWh €58-60 /MWh	0.0% (-)	€0/MWh €60-120 /MWh	-	€0/MWh €0/MWh	-	-	0%	-	-
Poland	€0/MWh €57-61 /MWh	0.2% (mandatory quotas)	€0/MWh €60-100 /MWh	0.2 % (mandatory quotas)	€0/MWh €15-75 /MWh	-0.15 % (mandatory quotas)	€0/MWh €30-40 /MWh	10.1 % (mandatory quotas)	-	-
Slovakia	€29/MWh €60-70 /MWh	0.15 % (maintenance tariffs)	€30/MWh €60-100 /MWh	-	€30 /MWh €15-100 /MWh	-0.05 % (fiscal incentives and subsidies)	€29/MWh €29-40 /MWh	4.80 % (maintenance tariffs)	-	-
Slovenia	€58/MWh €59-69 /MWh	0.0% (-)	€79/MWh €60-100 /MWh	0.5% (maintenance tariffs)	€64/MWh €18-98 /MWh	0.9% (maintenance tariffs)	€61/MWh €40-60 /MWh	5.1 % (maintenance tariffs)	-	-

Source: EC (2007).

Table 3: *Best practice examples in the EU states*

	general	solar, thermal	photovoltaic	biomass	wind	hydro	geothermal
Austria	Quotas for producers	Compensation schemes	Compensation schemes, maintenance tariffs	Compensation schemes, maintenance tariffs, tax allowances	Maintenance tariffs	Compensation schemes and mandatory quotas	Compensation schemes and maintenance tariffs
Germany	High maintenance tariffs	Compensation schemes	Maintenance tariffs	Compensation schemes, maintenance tariffs	Maintenance tariffs, tax allowances	Maintenance tariffs	Compensation schemes
Denmark	Compensation schemes, maintenance tariffs	Compensation schemes, mandatory quotas	No specificity	Compensation schemes, maintenance tariffs	Maintenance tariffs, tax allowances	No specificity	No specificity
Finland	Compensation schemes, energy tax exemptions	Compensation schemes	No specificity	Compensation schemes, energy tax exemptions	Compensation schemes, energy tax exemptions	Compensation schemes, energy tax exemptions	No specificity
Italy	Mandatory quotas min. 8 % offers	Fiscal incentives and mandatory schemes	Compensation schemes, quotas, CO_2 taxes	quotas, CO_2 taxes, tax exemptions	quotas, CO_2 taxes	quotas, CO_2 taxes	quotas, CO_2 taxes
The Netherlands	Energy tax exemptions, fiscal incentives	Compensation schemes, fiscal incentives	Compensation schemes, energy tax exemptions, fiscal incentives	Energy tax exemptions, fiscal incentives	Compensation schemes, energy tax exemptions, fiscal incentives	No specificity	No specificity
Sweden	Tax exemptions	Compensation schemes	No specificity	Compensation schemes, tax exemptions	Compensation schemes, tax exemptions	Compensation schemes	No specificity
Spain	Compensation schemes, maintenance tariffs, financing, third parties	Compensation schemes, fiscal incentives	Compensation schemes, fiscal incentives, maintenance tariffs	Compensation schemes, fiscal incentives, maintenance tariffs	Maintenance schemes	Maintenance schemes	Compensation schemes

Source: Euroelectric (2004), Directive 2003/96/EC.

Austria. In November 2007, Austria complemented amendments of its existing RES policy (Ökostromgesetz Eco-Electricity Act 2003, Ökostromnovelle 2008) and integrated the allocated budget (per sources) for the RES investments. The competent authority is obliged to buy electric power and to pay the maintenance tariffs. By 2005, the tariff system encouraged the increase of the utilisation of wind, biomass, and small hydroelectric plants. Since 2006, incentives of this kind have stagnated. The amendments from the year 2008 could contribute to the reduction of investments in RES. Austria has set the objective of attaining 34 % of the energy share from RES by 2020. Its objective is also to reach higher capacities of wind energy and hydro-energy (700 MW by 2015).

Denmark. The utilisation of RES in Denmark has been encouraged since 1980, especially with regards to wind and biomass energy. The maintenance tariffs have been available for various technologies, starting with the encouragement of the utilisation of the wind energy in 1980. The Electric Power Offer Act and the RES Utilisation Support Act entered in force in 1981. Combustible wastes and biofuel have been increasingly used since 1987. Investment subsidies were provided in years 1979-1989 and 1981-2001. The capital grants for the facilities driven by wind energy, biomass and biofuel represented 15-30 % of the value of the investment costs. The Biomass Utilisation Act entered in force in 1993 and was modified in 2000.

Denmark has set a goal of achieving a share of 29 % of gross electric power consumption from RES by 2010. In the period from 1990 to 2006, the country promoted the utilisation of RES primarily by means of maintenance tariffs. Since 2000, they have applied premiums, public schemes (public tenders), and voluntary agreements. Subsidies acting as an instrument were relevant until 2000. In 2000, Denmark introduced environmental premiums for facilities, driven by the (coastal) wind energy, and thus the market price of the MWh increased for the environmental premium (13 €/MWh), accompanied by the compensation of the generation costs (3 €/MWh) for the period of 20 years. Subsequently, the country extended the environmental premiums to facilities, driven by the wind energy in the interior of the country. A mandatory quota of the utilisation of one million tons of straw was introduced in 2005. In 2006, the producers of electric power obtained in total €57/MWh through schemes in the western part of Denmark and approximately €58/MWh in the eastern part of the country. The maintenance schemes (for the utilisation of wind energy) in years 2002 to 2005 were used for energy facilities with the installed power of 750 MW hours. In 2006, the latter were replaced by the maintenance scheme for wind facilities with the power of 200 MW (the countervailing price amounts to €70/MWh for 50,000 hours of full load). However, the loads above this value reduce the tariff to the current market price for MWh. The state guarantees subsidies, maintenance tariffs, premiums and public tenders. Furthermore, the CO_2 taxes on biofuel were eliminated in 2005. In Denmark, the maintenance tariffs are paid for the period of 20 years in the amount of €13 /MWhe (+€3/MWhe for the balancing of costs for electric power generation from wind). The maintenance tariffs on biofuel, however, amount to €80/MWhe for the first 10 years of operation and €54/MWhe for 11 to 20 years of operation.[5]

In 2008, the Danish company DONG turned to the German company Siemens, for assistance in the construction of the largest windmill field, designed to provide 1.800 MWe of electric power (which could cover the needs of an average American town). The project is estimated to cost

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[5] Specifika Danske je, da poznajo davke na gorivo za ogrevanje in ne davkov za gorivo namenjeno pridobivanju el. energije. Električna energija je predmet davkov na potrošnjo. Energetski objekti pogosto kogenerirajo el. energijo in toplotno energijo.

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four billion dollars and the windmills will most probably be installed somewhere by the North Sea. Denmark will thus strengthen its top position among the countries, intensively using solar energy (Act on RES, 2004).

Italy. Italy has enforced the practice of mandatory quotas (Legislative Decree 29/12/2003 No. 387, Article 11). A large amount of electric power in Italy is obtained from hydroelectric power plants, while much is still generated from fossil fuels. Italy wishes to raise the share of biomass, wind and solar energy. The policy of RES is integrated with the policy of the reduction of CO_2 emissions. In 2001, Italy introduced a system of green certificates for producers or importers of electric power. The initial requirement was 2 % from the generated or imported electric power, later on the requirement increased by 0.35 % per year by 2006, and by 0.75 % annually from 2007 to 2012. The set objective is 25 % of gross consumption of electric power coming from RES by 2020. Providers of electric power are obliged to provide a certain target share from RES. The objective for biofuel, introduced in 2008, was 3 % by the end of 2009 (in compliance with the EU Biofuel Directive).

Finland. In order to facilitate investments in RES, Finland provides guarantees, subsidies, reimbursement of 30 to 40 % of investment costs (for wind energy), tax exemptions for biofuel and increased taxes for facilities, generating energy with high emissions of $CO_{2,}$ as well as tax exemptions for facilities, generating energy from RES (Act on Verification and Notification of Origin of Electricity, Electricity Market Act 2005). The action plan of RES in Finland aims to increase the competitiveness of RES technologies. The energy tax imposed on fossil fuels, and investment incentives demonstrate short-term effects, while strong incentives of research work will show effects in the long run. The objective is to achieve a generation share of 28 % of the electric power from RES by 2020, and 31.5 % of the gross electric power consumption from RES by 2010. The biofuel share should amount to 5.75 % by 2010. The most represented utilisation in Finland is the utilisation of hydro energy (50%) and the utilisation of biomass (48%). The utilisation of waste has also increased.

France. In France, the promotion of investments in RES is predominantly a combination of maintenance schemes and multiple tax exemptions; for facilities exceeding 12 MW (except for wind energy), there are also public tenders. The programmes may vary according to regions and their geographic specificities. Maintenance tariffs were introduced in by the legislation 2000/108 (Modernisation and Development of Public Services in Energy Sector Act), followed by legislation modifications in 2005/781 (Programmes of Energy Policy Orientation). The law now ensures fixed maintenance tariffs for all RES energy generation facilities with installed power of maximum 12 MW and for wind-energy facilities. At the same time, electrical energy suppliers are obliged to purchase it from RES producers. Tariffs or premiums vary between alternative technologies (by taking into account inflationary corrections).

In France, tax allowances and maintenance tariffs represent the most important instrument (introduced in 2001, modified in 2002 and 2005). Before that, subsidy schemes were used. France set out the aim of producing 23% of electrical energy from RES, in compliance with the EU Directive, and of gross consumption of 21% of electrical energy from RES by 2010. By 2015, the share of biofuels should reach 10%. Currently, 11% of gross consumption of electrical energy is covered by RES (mainly by hydro-electric power stations). Wind utilisation has been growing since 2005 and photovoltaics, through maintenance tariffs, since 2006. Currently, 10.1 Mt (2005) of heat is produced from RES. Biomass potential is underutilised. In France, the liquid fuel market is the second largest market in the EU.

Since July 2007, maintenance tariffs have been granted only to new energy-generation facilities within the areas intended for their installation. The tariffs are usually fixed for the first ten years. They are modified subsequently according to electrical energy production (or full working hours per year), whereby higher tariffs apply to lower production. The tariff for coastal wind is €82/MWh for ten years (mainland France). In a period of five years, tariffs vary in the following range: €28/MWh (≥ 3600 hours/year), €68/MWh (2800 hours/year) and €82/MWh (≤ 2400 hours/year). A tariff of €130/MWh only applies to the first ten years. The following also applies: €130/MWh (for ≤ 2800 hours/year), €90/MWh (3200 hours/year) and €30/MWh (≥ 3900 hours/year). For biomass, the following applies: if the actual production of electrical energy is lower than the guaranteed electrical energy amount: RT x (0.575 + 0.5 x d) + M, if the object operates 85% of the time or more, RT x (0.15 + d) + M, if the objects operates less than 85% of the time, whereby RT is the reference tariff (between €49 and 55/MWh according to the geographic location), d is availability (between 0 and 1) and M the premium (depending on V value: indexed thermal energy + indexed electrical energy / according to the energy generation facility output): if V ≤ 40 %, M = €0/MWh; if V = 50%, M = €5/MWh; if V = 60%, M = €10/MWh and if V ≥ 70%, M = €12/MWh (intermediate values are extrapolated). If the actual production of electrical energy exceeds the guaranteed production, d = 0.15 is taken into account. Tariffs for photovoltaics were set in 2006. In 2007, the maintenance tariff for wind and biomass energy utilisation was €86/MWh on average (for wind objects above 12 MW, for biomass above 216 MW and for biofuel above 16 MW).

Fiscal incentives are applied in the sense of tax allowances and reduced tax rates (from 33% to 5.5% - 19.6%) on corporation profits, fixed assets write-off and investments in the first 12 months (before January 2007). Maximum state guarantees for investments should not exceed €750,000 covering not more than 70% of the loan. Among RES promotion measures, favourable interest on bank loans (in 2008, interest rate was 2.75%) should also be emphasised. The ADEME programme was providing financing for up to 80% of RES investment until 2005, when tax allowances were introduced and co-financing share was reduced.

Germany. Germany can be said to have an extremely transparent system of promoting investments in RES. Maintenance tariffs are provided for a period of 20 years (for small-sized hydroelectric power stations for 30 years, while for medium-sized ones for 15 years) and represent the most important stimulation instrument. Annual reduction of incentives additionally promotes faster investment in RES facilities (Revision of the Renewable Energy Law, which entered into force in April 2004). National banks provide soft loans to investors, while financial intermediaries created an attractive investment portfolio for RES objects and have thus also attracted private capital. In 2005, tax incentives were introduced (within the framework of federal Tax Law), while federal energy investment funds were abolished.

Germany introduced maintenance tariffs as early as 1991. In the period 1991-2000, the tariff was uniform and mainly promoted wind energy (De Jager and Rathmann 2008). Rapid development of alternative technologies dictated implementation of *Erneuerbare Energien Gesetz – EEG* (the Renewable Energies Act), which entered into force in 2000 and was amended in 2004. It provided priority network access, priority maintenance tariffs and determined payments for RES alternative technologies.

The structure of maintenance tariffs is adapted to the cost cycle of producing electrical energy from RES, which also contributes to reducing investment costs. In this manner, not only are cost-efficient RES technologies promoted but RES in general. Profitability and yield of RES capacities or technologies are thus conditional upon the tariff structure.

For RES electrical energy producers, priority network access means less risk of "shallow" or inaccessible networks. Nonetheless, the operator's costs and price of electrical energy for clients are thus increased. Since network enhancement and infrastructure fall short of the RES technology development, *Gesetz zur Beschleunigung der Infrastrukturplanung*, the Promotion of Infrastructure Planning Law was adopted in November 2007, setting out responsibilities for costs of poor integration or access of RES energy facilities to the network. Thereby, the total cost of infrastructure investment decreased and operators are given more favourable financing conditions. In Germany, an energy operator may also prevent a RES energy generation facility from accessing the network if the network has already been saturated with electrical energy from other RES energy generation facilities, which means loss of income.

National banks finance investments into RES energy generation facilities up to 75% of their value and to a maximum of 10 million EUR. Loans are usually approved for 10 to 20 years at an interest rate lower (by 0.5 to 1.5%) than the capital market interest rate. Loan conditions vary according to RES investment specificities and according to banks. Individual financing schemes also favour certain RES investments.

Fiscal incentives mean reduced tax rate on corporation profits for a period of 10 to 20 years. Taxpayers had the possibility to choose between linear and degressive method of calculating reduced tax rates (in 2006 and 2007, tax relief amounted to maximum 30%).

The Netherlands. The most important measures are maintenance schemes, tax allowances and soft bank loans. Since July 2003, maintenance premiums have been paid selectively on the basis of technologies for a period of ten years at a peak market price for electrical energy (with a maximum of 20,000 full operating hours for wind-power facilities). Premiums are adjusted on an annual basis. In May 2005, premium sums for biomass facilities were determined (> 50 MWe) and wind-power facilities were close to 0. The reason for such a measure was a lack of resources to this end due to strong development of farms with wind-power facilities (this budget is partially co-financed by fees paid by electrical energy users fixed once per year). Since August 2006, growth of investments in RES facilities has slowed down slightly due to subsidy reduction. In April 2008, maximum premiums were introduced (the legislation *Regulation Guarantees of Origin for Renewable Electricity* entered into force in December 2003). In the Netherlands, premiums for newly registered facilities were set to 0, since normal operation of all constructed facilities would otherwise attain the target share of electrical energy obtained from renewable energy sources.

For facilities producing both electrical energy and heat, producers receive subsidies for costs in the amount of 20 €/MWh. Fiscal incentives are also being implemented; the general tax rate of 29.6% on corporation profits is reduced by a few percentage points (to 25.5% for the first €22,689 of profit before taxes, 2006). The EIA scheme (Energy Investment Allowance)[6] enables the investors in RES to deduct investment value from the taxable profit. In addition to the reduced tax rate and base, the tax base may also be reduced by 44% of investment costs in the first year. On average, it is estimated that total benefit arising from all fiscal incentives amounted to 11-13% reduction of investment costs (whereby in 2006, average RES investment

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[6] The EIA budget is determined for each year and does not change. In 2006 and 2007, it amounted to 139 million EUR. If the resources are completely disbursed, the Ministry of Finance may revoke or temporarily stop disbursements until the next year and new budget.

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costs of companies ranged between 2.1 million EUR and 108 million EUR). Fiscal incentives are also combined with other measures. From the perspective of rationalising investment costs for wind-power technologies, costs amounting to maximum €1100/kW for coastal wind energy generation facilities and €2250/kW for mainland wind energy generation facilities were deemed to be acceptable.[7]

The approved loan interest rates for RES investments are, on average, one percentage point lower than commercial interest rates and more than 70% of income from the title of RES investments is partially exempted from the tax base, which makes such investments attractive. Minimum loan amount is €22,689, while the maximum is €34,033,516.

Sweden. Sweden made a good promotion of RES and combined energy taxes with environmental bonuses as early as 2003. In May 2003, green certificates were introduced with a view to contributing to improved energy efficiency of RES technologies. The target share was set to 49% of electrical energy from RES by 2020 and to 60% of gross consumption of electrical energy by 2020. Parliament decided to increase RES by 10 TWh per year between 2002 and 2010, which corresponds to the target share of 51% by 2010. In June 2006, the target of increasing electrical energy obtained from RES in TWh was set for the period between 2002 and 2016. The target share of increasing biofuel consumption is 5.75% by 2010. Most of the produced electrical energy is obtained from hydro sources, which currently make 38% of RES energy. Biomass utilisation is relatively low. The same applies to wind energy (policy of promoting wind power utilisation is similar to the policy implemented in the eastern part of Denmark – Electricity Certificate Act, SFS 2003).

Spain. A transparent system provides the investors with long-term security. Wind power is being intensely utilised and in 2007, upper and lower limits of premiums were implemented (*Orden* ITC/1522/2007", Decision ITC/1522/2007, May 2007, *Boletín Oficial del Estado 131*, Official Gazette, June 2007).

In 1997, a programme of RES investment support was introduced in Spain, which contributed mostly to increased utilisation of wind power. Maintenance tariffs and premiums were high and the system was transparent. Spain set out the aim of achieving a share of 29.4% of gross consumption of electrical energy from RES by 2010 and 30.3% of energy from renewable energy sources by 2010, including contribution of wind power with capacities of 20,155 MW, photovoltaics with capacities of 400 MW, solar thermal energy with capacities of 4.2 million m^2, solar thermal electrical energy (500 MW) and biomass (1,695 MW). In 2005, biofuels and other alternatives for transport reached (according to the Directive on biofuels 2003/30/EC) a share of 0.40%. The national programme envisages increase in this share to 5.83% by 2010.

***Table 4:** Review of policies to promote investments in renewable energy sources in EU-15*

Country	Incentive scheme	Measures
Austria	Maintenance tariffs combined with regional investment incentives.	Maintenance tariffs were provided for a period of 13 years. The instrument was efficient for new installations with a permit valid until December 2004. Active period of the system was not extended nor replaced by an alternative instrument. Since May 2006, maintenance tariffs have been provided for 10 years, and in the share of 75% to 50%, for 11-12

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[7] The data indicate that for coastal wind, 85% of RES facilities are within the range of cost efficiency, and for mainland wind, 65% of all RES projects are energy efficient.

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		years. Since May 2006, budget for investments in RES has been reduced. Tax exemption for biofuel amounts to 95%.
Belgium	System of combined quotas/system of trading with green coupons combined with minimum price of electrical energy produced from renewable sources (RS).	The federal government set a minimum price for electrical energy produced from RS. Flanders and Wallonia introduced a system of mandatory quotas as an obligation of electrical energy producers. At the federal level, mainland wind utilisation is also encouraged. Investment subsidies amount to 10-20%. Tax exemption applies for fuel containing at least 2.45% biofuel and 7% ethanol.
Denmark	Maintenance tariffs and premiums, tenders for using mainland wind power.	The agreed prices are valid for a period of 10-20 years (according to the technology). The agreed maintenance tariffs are lower than they used to be. A greater emphasis is given to biomass exploitation.
Finland	Energy tax exemptions combined with investment incentives.	Tax reimbursements and investment incentives up to 40% for wind power and up to 30% for electrical energy produced from RS.
France	Maintenance tariffs	For energy generation facilities < 12 MW, maintenance tariffs are provided for a period of 15 to 20 years (hydro-energy and photovoltaics). For energy generation facilities > 12 MW, tender scheme is relevant. Investment subsidies amount to 40%. Tax reduction (from 1998) and long-term capital subsidies.
Germany	Maintenance tariffs	Maintenance tariffs are provided for a period of 20 years (Renewable Energy Sources Act) as well as tax incentives, exemptions and soft loans.
Greece	Maintenance tariffs combined with regional investment incentives. Since 2007, subsidies for alternative energy sources have amounted to €73 to 90 /MWh and for photovoltaics €230 to 500 /MWh.	Maintenance tariffs are provided for a period of 12 years (with a possibility of further extension to 20 years), while investment incentives amount up to 40%.
Ireland	Tender schemes for exploitation of RS. Public tender system was replaced by maintenance tariff system.	Tax incentives for producing electrical energy from RES, public tenders, maximum prices. Maintenance tariffs for biomass, hydro-energy and wind were introduced in October 2006 for a period of up to 15 years. The last year for the introduction of fiscal incentives is 2009, as incentives are no longer envisaged after 2024. Purchase price for electrical energy obtained from RES is subject to negotiations between producers and suppliers.
Italy	System of mandatory quotas/system of trading with green coupons. Maintenance tariff system for photovoltaics from 5 August 2005.	Certificates are being issued only for the first 12 years of operation of energy generation facilities using alternative energy sources, except for biomass, where certificates for 100% production of electrical energy for the first eight years of operation and 60% for the following four years are given.
Luxembourg	Maintenance tariffs	Maintenance tariffs are provided for a period of 10 years (20 years for photovoltaics) and investment incentives are also available.

The Netherlands	Maintenance tariffs	Maintenance tariffs are provided for a period of 10 years (since June 2003) and fiscal incentives, tax exemptions (since 2006) and mandatory quotas since 2007. For each produced MWh of electric energy, the producer receives a green certificate, which is the basis for premium disbursement. Premiums are also defined for biofuel utilisation (<2MWe). In 2008, premium system for RES was improved.
Portugal	Maintenance tariffs combined with regional investment incentives.	Investment incentives up to 40%. Tax reduction and possibility of tax allowance transfer. Maintenance tariffs are provided for a period of 15 years of RES facility operation, their amounts depending on the share of peak or base energy, source, inflation, etc.
Spain	Maintenance tariffs	Fixed maintenance tariff or premium at the peak, conventional prices of electrical energy available throughout operational period of RES energy generation facility. Investment subsidies amount to 36%, there are tax relieves for biodiesel fuel. The system has been designed in a transparent manner and combines several measures at the same time. Incentives are not limited in time, with an exception of fixed tariffs, which are limited to a period of 15 to 25 years (depending on the technology).
Sweden	System of mandatory quotas/system of trading with green coupons.	System of mandatory quotas is obligatory for electrical energy users. Investment incentives and environmental bonuses are available for energy investments in wind power.
Great Britain	System of mandatory quotas/system of trading with green coupons.	System of mandatory quotas is obligatory for electrical energy suppliers (companies not fulfilling obligatory regulations of required RES electrical energy production are subjects to a fine). Tax exemptions for subcontractors using RES are available as well. Tax relieves on biodiesel fuel and mandatory quotas have been valid since April 2008. Mandatory share of RES energy is increasing until 2015.

Source: Euroelectric (2006), EcoFys (2008), LEI (2008).

2 DRAWING UP RECOMMENDATIONS FOR CREATING STIMULATING FISCAL POLICY TO USE RENEWABLE SOURCES IN ELECTRICAL ENERGY PRODUCTION

A. EU Directives to increase investments in renewable energy sources.

Directive 2001/77/EC promotes higher yield of RES in internal markets. The target is to attain at least 12% of gross consumption of electrical energy from RES by 2010. The Directive also set out the establishment of adequate institutions to promote RES investments as well as providing stimulation schemes at the national level (price schemes, system of quotas and fixed prices, subsidies by kWh, tax incentives and allowances, assistance in financing capital investment, promotion of development and research of new technologies and facilities). The Directive COM 2005/627 on electrical energy from renewable sources and the Directive COM 2005/628 on the biomass action plan followed. The Directive COM 2006/848 deals with a comprehensive approach of RES investments with respect to climate change. The comprehensive approach of RES investments was upgraded by the Directive from 2008 (proposal for the Directive 2008).

The quota system is based on two options, *green certificates* and *public tenders*. The green certificates are being sold at market prices with a view to providing coverage of additional costs of producing electrical energy from RES (Belgium, Sweden, Great Britain) and providing the required share of electrical energy from RES. The green certificates therefore promote the consumption and production of electrical energy from RES by setting out a compulsory share of production or consumption of electrical energy from RES.

The state may also publish a tender for supplying electrical energy from RES at a price defined in the tender. Overspending in energy production above the bid price is transferred to the end user of energy in the form of a tax (example of Ireland and Great Britain). In case of a fixed price scheme, the quota and maximum limit have not been directly set and the quota is created indirectly according to the price. The premium mechanism means that state sets a fixed premium or environmental bonus which is paid above the normal price of electrical energy (example of Germany, Spain, Denmark and France). Where prices correlate with market prices, there are no major differences between premium prices and market prices. The state adapts the premiums to the changing costs of electrical energy production. In case of fixed maintenance schemes, all electrical energy from renewable sources that has been sent to the network is also distributed and sold at a guaranteed price (which is above the normal price). The burden is assumed by the end user through the distribution tariffs. The state provides direct subsidies thus covering a part of costs of the capital or of the production of electrical energy from RES. Tax allowances or exemptions are available in case of investments in a demanding RES technology. Fiscal incentives for the utilisation of electrical energy from RES (reduced VAT, tax allowances for investing in RES facilities, energy tax reimbursements or exemptions, $CO_{2,}$ NO_x, SO_2 taxes as a direct stimulus for investment in RES energy generation facilities, subsidies per kWh of production costs or electrical energy prices or investments in energy generation facility) are also recommended.

In December 2008, the European Commission indicated the importance of increased energy efficiency and acceptable CO_2 emissions in order to diminish the economic crisis (SEC 2009/268, 269, 270). Information and communication technology should additionally contribute to energy efficiency and economic consumption of energy and energy-generation products (COM(2006) 545; COM(2008)30, Directive 2005/32/EC, COM(2008) 16, 17, 19, 772, 241, COM(2008) 397, 780, 800, 886, 607), which would be manifested in all segments of energy users (energy-saving products, rational behaviour of energy end users, lifestyle, RES utilisation, regulatory improvements of energy transfer, reduced losses in transfer, energy-saving investments, integrated rationalisation of energy consumption by energy generation facilities and end users, energy-saving construction of facilities, promotion of research and development of new energy-saving technologies).

B. Implications for energy policy of RES in Slovenia.

Based on all of the above, implications for energy policy can be summarised in:

1. the reduction of capital costs in establishing market conditions and stimulation schemes corresponding to technical efficiency and life span of facilities,
2. corporate financing under more favourable conditions is reasonable considering the large investment (with a life span of 20 to 40 years),
3. financing and maturity (according to RoE) should depend on risks of RES technologies,
4. bank warranties should improve financing conditions in potential co-investment,
5. it is appropriate to combine several measures simultaneously (tax exemptions and allowances, subsidies) and promote investments in RES corresponding to geographic, meteorological and batimetric conditions,

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6. long-term orientation of incentives and providing certainty to investors in RES, depending on the life span of RES technologies,
7. tax incentives and allowances should be conditional upon the life span of the technologies and should reduce costs of producing energy from RES,
8. initial tax incentives and allowances are the most important, as they maximally reduce costs of operation and prices of kWh,
9. combining instruments relating to production and demand for electrical energy from RES,
10. combining fiscal incentives (tax allowances, exemptions and deductions of the amount of an investment from tax base) contributes to reducing RES investment costs,
11. guarantees of the state for investments in RES reduce capital costs.
12. participation of the state or participation in investments in RES has several advantages:
    - project implementation risk is reduced below the conventional risk of investors and creditors,
    - capital costs are reduced,
    - investment subsidies can change into shares or participation of the state, which means government revenue from this title in the future,
    - dispersed financing and required lower yield (due to higher significance of the public interest),
    - participation increases return reactions and faster adaptation of the regulation to the needs of optimum RES investment implementation,
    - adaptation of the economic policy to the actual needs of the market,
    - faster adaptation of energy infrastructure to the needs of RES facilities.

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CAVITATION SWIRL AT THE ENTRANCE OF CENTRIFUGAL PUMP

KAVITACIJSKI VRTINEC NA VSTOPU V RADIALNO ČRPALKO

Andrej Predin[1], *Boštjan Gregorc*[2], *Ignacijo Biluš*[3]

Keywords: cavitation, centrifugal pump, computational fluid dynamics

Abstract

The trend toward higher speed and power in order to achieve high performance characteristics has inevitably increased the potential for operating instabilities in modern pumps. Even in the absence of cavitation and its complications, these phenomena can lead to performance loss and, in the worst cases, to structural failure.

One of the major sources of instability in a centrifugal pump is, as mentioned, cavitation within the pump. Cavitation of a centrifugal pump is the result of insufficient net positive suction head and can occur within the entire range of operating conditions. Cavitation may cause three different and undesirable effects: (a) a drop in head and efficiency curves, (b) damage to the impeller by pitting and erosion, and (c) structural vibration [2] and resulting noise [1]. Therefore, the cavitation process must be prevented by all means. This paper deals with the influences of a simple motionless four-blade guiding device on the cavitating characteristics of radial pump.

In the case of cavitating flow regimes, three distinct operating possibilities are known: (a) the stable regime, in which the majority of cavitating centrifugal pumps operate, (2) the unstable regime described as hydro-dynamically induced cavitation surging, and (3) the transient regime, described as thermodynamically induced surging [2].

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[1] Prof. Andrej Predin, PhD., Faculty of Energy Technology, University of Maribor, Hočevarjev trg 1, 8270 Krško, e-mai: andrej.predin@uni-mb.si

[2] Boštjan Gregorc, (engineering), Dravske elektrarne, Tel.: +386 (0)2 300 5295, Fax: +386 (0)2 300691, E-mail address: bostjan.gregorc@dem.si

[3] Ignacijo Biluš, Ph.D. Faculty of Mechanical Engineering, University of Maribor, Smetanova 17, 2000 Maribor, e-mail: ignacijo.bilus@uni-mb.si

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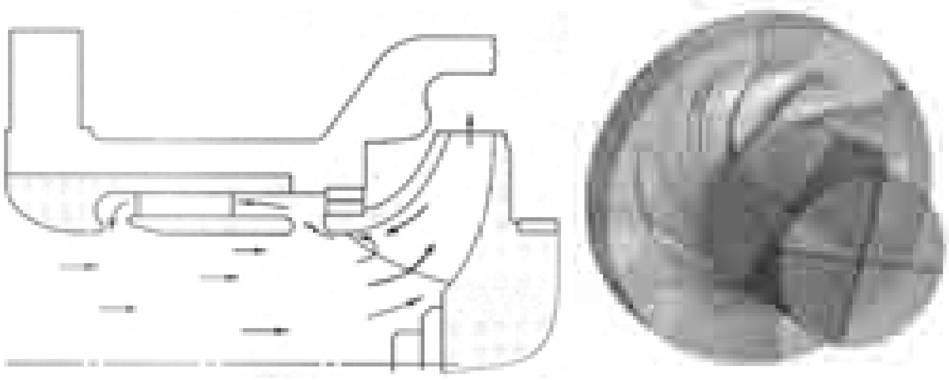
Povzetek

Trend k večji hitrosti in moči ob doseganju visokih zmogljivosti neizogibno poveča možnosti za nestabilno obratovanje sodobnih črpalk. Celo v odsotnosti kavitacije in z njo povezanih zapletov, lahko ti pojavi povzročijo izgube oz. nižajo učinkovitost črpalke in v najslabšem stanju povzročajo tudi erozijo materiala. Eden od glavnih virov nestabilnosti v centrifugalne črpalke je kavitacija v črpalki. Praviloma se pojavi zaradi nezadostne neto pozitivne sesalne višine pri nižjih pretokih, lahko pa se pojavijo tudi v celotnem območju obratovanja. Kavitacija praviloma lahko povzroči tri različne neželene učinke: (1), padec obratovalne karakteristike in izkoristka črpalke, (2) povzroča škodo na rotorju z erozijo materiala rotorja, ter (3) vzbujanje strukturnih vibracij [2] in posledično večanje obratovalnega hrupa [1]. Zato je treba preprečiti proces kavitacije z vsemi možnimi sredstvi. Pričujoči članek se ukvarja s preprostim ukrepom za znižanje vpliva kavitacije in kot se je izkazalo učinkovitimi vodilnimi lopaticami postavljenimi v ustje črpalke oz. vstopnega cevovoda.

Pri kavitirajočem toku smo opazili tri, že znane obratovalne režime in sicer (1) stabilni obratovalni kavitacijski režim, pri katerem obratuje večina centrifugalnih črpalk, (2) nestabilni režim, ki predstavlja hidrodinamično vzbujene kavitacijske tokove in (3) tranzientni režim, ali termodinamično vzbujeni kavitacijski tokovi [2].

1 INTRODUCTION

Hydro-dynamically induced surging can occur at low values of capacity in almost all centrifugal pumps. The onset and intensity of cavitation surging is primarily determined by the shape of the impeller blades at the impeller inlet. The extent to which cavities travel away from the impeller is determined by inlet pipe geometry. In most impeller-pipe configurations, the low pressure regions are localised and backflow recirculation giving rise to cavitation surging hardly leaves the inlet blade region. In some pumps however, particularly those for which the inlet pipe has axial symmetry with an impeller eye, the associated backflow extends well into the inlet pipe. It is known that in pumps, where a backflow recirculation device (Figure 1) is fitted, the intensity and extent of surging is much reduced over a wide flowrate range.



a) b)

Figure 1: *Backflow recirculation system (a) and simple axial flow guiding device in front of centrifugal impeller (b)*

Another known powerful method of improving the cavitation performance is the attachment of an inducer just upstream of the main impeller [3]; many researchers all over the world have studied different versions of pump inducer geometry in order to achieve reliable and cavitation-free operating characteristics [3], [4].

According to relatively complicated “pipe in pipe” construction of backflow recirculation systems and regarding the pump inducer price, the simplified flow guiding device shown in Figure 1 was used for cavitation surging decrease. The main advantage of presented system should be its simple design and low price.

2 GEOMETRY OF PHYSICAL MODEL

A simple copper cross in the form of four guiding blades with inclination angle α=20º was placed into the transparent pipe at the impeller entrance. The guiding blade lengths were equal $l = 1.15D$, where D present the inlet pipe diameter.

The flow guiding pipe system was connected to a conventional closed loop pump testing installation as shown in Figure 2.

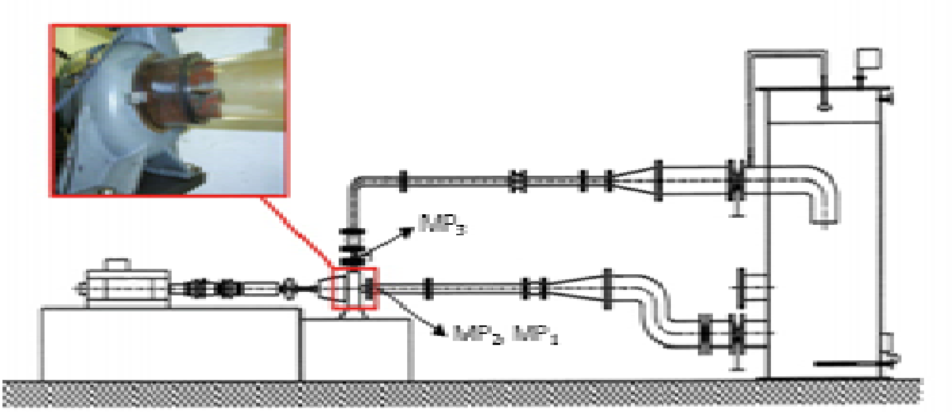
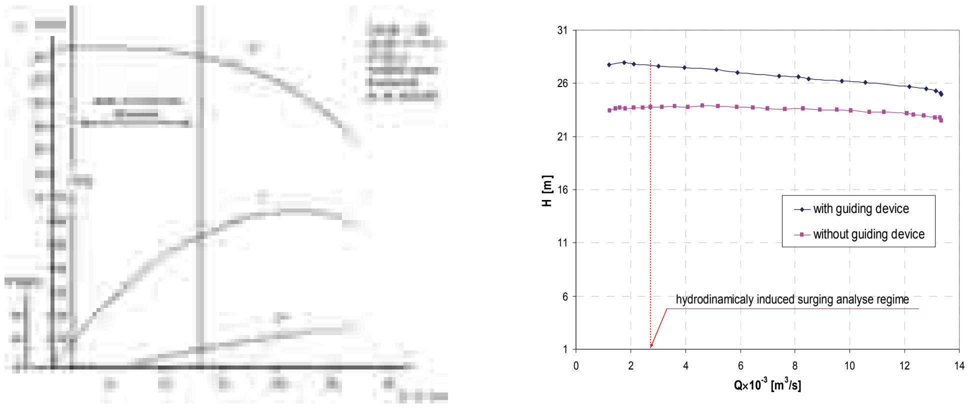


Figure 2: *Measuring system drawing.*

For test purposes, a commercial radial water pump with design speed of 2,900 rpm, maximal capacity $Q_{max} = 0.027\ m^3/s$ and maximal head $H_{max} = 25m$ was used. The operating characteristics of the pump are shown in Figure 3 (a).

Figure 3 (b) shows the measured pressure difference curve agrees with operating characteristic defined by the pump manufacturer Figure 3 (a) in the case of conventional inlet pipe geometry. It is also evident that the guiding vanes device increases the achieved pressure difference at the flow rates up to $Q = 0.5 \cdot Q_{\max}$. The reason for this could be found in the better flow attack angles at the pump inlet.



(a) **(b)**

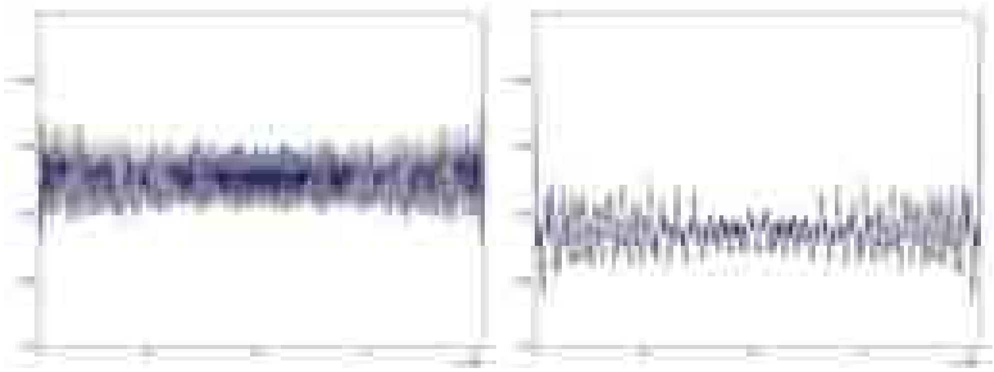
Figure 3: *Operating characteristics of tested pump (a) and measured influence* ***area*** *of guiding device on pressure difference curve (b).*

3 CAVITATION SURGE PRESSURE PULSATIONS

Pressure pulsations connected to cavitation surging were measured at the three different measuring points placed in the upstream (MP_2, MP_1) and downstream (MP_3) direction of the radial pump entrance pipe as shown in Figure 2. KELLER absolute piezo-resistive pressure transducers with pressure range up to 2 and up to 10 bar (FS) with a frequency response 20 kHz were connected to A/D measuring equipment. Pressure pulsations were analysed at different NPSH values of pump installation at flowrates equal to 12% of the flowrate at the best efficiency point (Q_{BEP}).

3.1 Measurements results

Normalised autocorrelation record of pressure distribution function was performed in order to show the periodic nature of the phenomenon. Figure 4 shows the results for different measuring points (MP_2 at $3 \cdot D$ and MP_1 at distance equal to $5 \cdot D$ from impeller eye).



a) MP1 at higher NPSH **b) MP2 at higher NPSH**

Figure 4: *Normalized autocorrelation of pressure distribution functions.*

Good correlation is evident from Figure 4, since the function values lie in the range from 0.991 up to 0.997. According to this, frequency analyses with Fast Fourier transformation (FFT) were performed for two different values of pressure in the water reservoir and different NPSH. The same operating regime was set for the example with and without a guiding device. Frequency analyses results records are shown in graphs from Figure 5 to Figure 9.

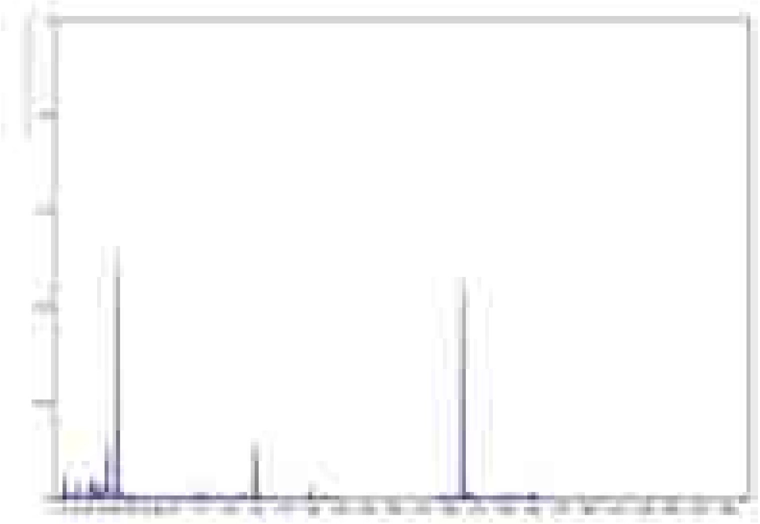


***Figure 5**: Pressure pulsations at MP_1 without guiding blades and higher NPSH value.*

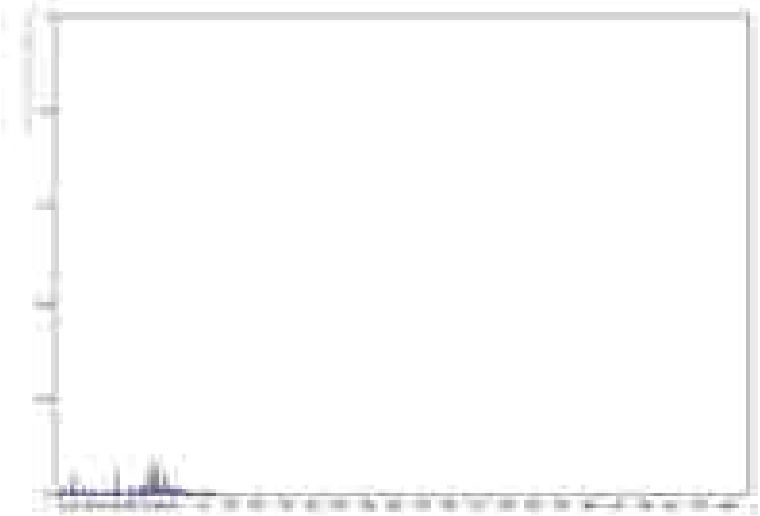


***Figure 6:** Pressure pulsations at MP_1 with guiding blades and higher NPSH value.*

It is evident from the frequency analyses presented in Figures 5 and 6, that guiding blades reduce the amplitudes at whole frequency range. This amplitude chocking is especially strong at rotating impeller basic frequency $f_{imp} \approx 50$Hz, its harmonics and blade passing frequency $f_{blade} \approx 300$Hz with its sub-harmonic.

These results confirm other authors' analyses defining the super synchronous speeds of rotating cavitation with range up to 1.4 comparing to impeller rotating speed [5].

Following the relative strong pressure pulsations at a distance equal to five pipe diameters (5*D*) from impeller entrance eye, a second measurement series was made at position MP_2 corresponding to a distance equal to three inlet pipe diameters (3*D*).

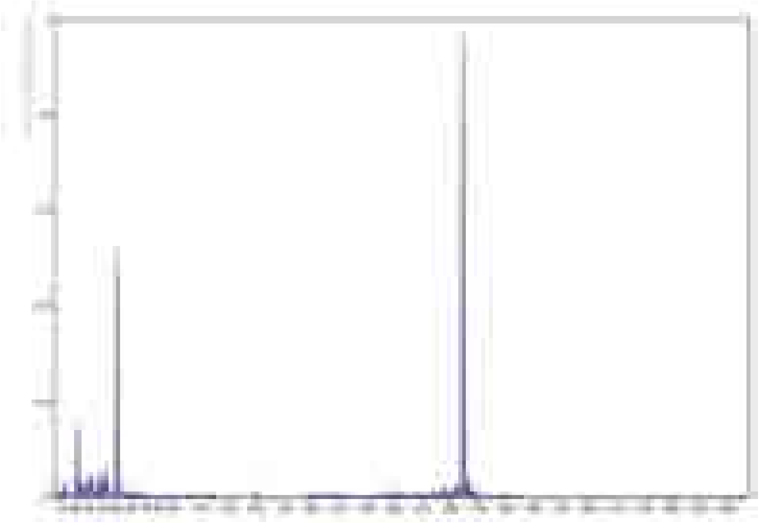


Figure 7: *Pressure pulsations at MP_2 without guiding blades and higher NPSH value.*

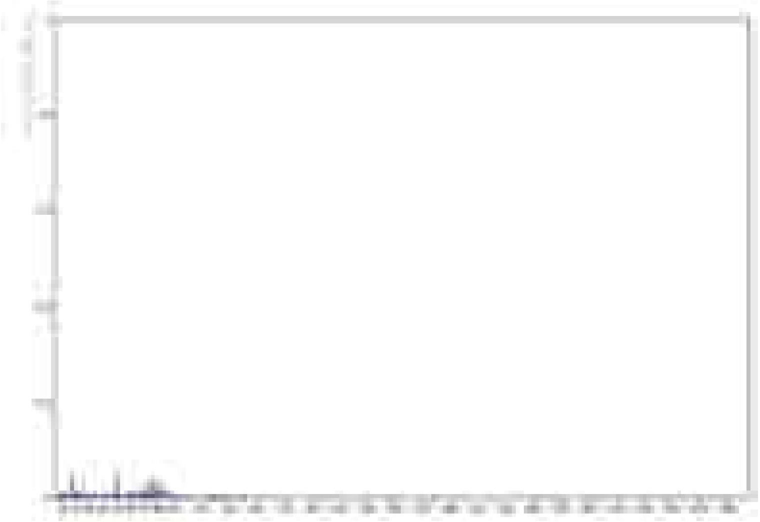
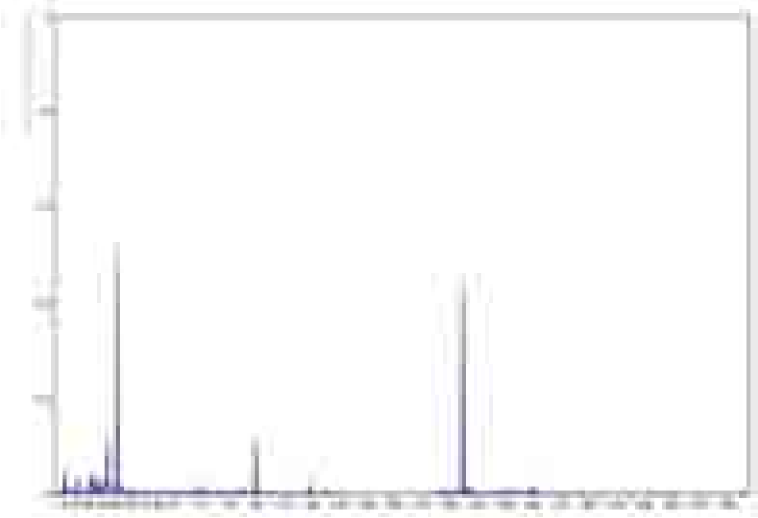


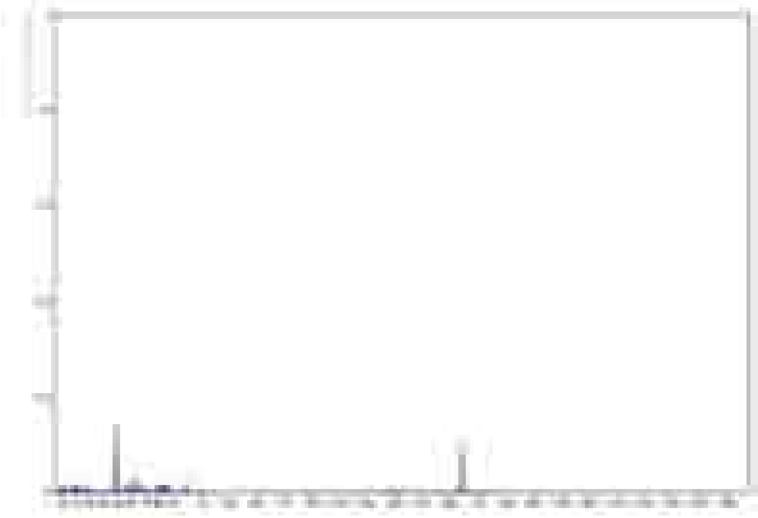
Figure 8: *Pressure pulsations at MP_2 with guiding blades and higher NPSH value.*

From the presented FFT analyses of pressure pulsations at MP_2, it could be concluded that the guiding device reduces pressure pulsation amplitudes of characteristic frequencies and hydro-dynamically induced surge pulsations with lower frequencies [2].

According to the distance dependency of pulsation measurements, an additional results comparison was made, analysing the influence of pressure values (NPSH) on pulsations. Figure 9 shows pressure pulsations at MP_1 and different values of NPSH.



a) Higher NPSH



b) Lower NPSH

Figure 9: *Pressure pulsations at MP_1 and different NPSH values without guiding blades.*

It is evident from Figure 9 that a pressure level decrease reduces the amplitudes of pulsations in the whole frequency range. The reason for this could be in the interaction of the complicated surge mechanisms with intensified rotating cavitation [5].

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4 NUMERICAL SIMULATION

Owing to the rapid increase of computer capabilities and according to intensive development of measurement methods, numerical simulation of cavitating (multiphase) flows has become possible in the recent years.

Homogenous flow, common flow field and other relevant fields such as temperature and turbulence are shared by both fluids (water and water vapour). This allows some simplifications to be made to the multi-fluid model. For a given transport process, the homogenous model assumes that the transport quantities (with the exception of volume fraction) for that process are the same for both phases.

A homogenous two-phase transport model included in commercial software ANSYS-CFX was used for surging simulation.

The Rayleigh-Plesset model is implemented in the multiphase framework as an interphase mass transfer model in used numerical code. The Rayleigh-Plesset equation provides the basis for the rate equation controlling vapour generation and condensation. The equation describing the growth of a gas bubble in a liquid is given by:

$$R_B = \frac{d^2 R_B}{dt^2} + \frac{3}{2}\left(\frac{dR_B}{dt}\right)^2 + \frac{2\sigma}{\rho_f R_B} = \frac{p_v - p}{\rho_f} \tag{4.1}$$

where R_B represents the bubble radius, p_v is the pressure in the bubble (assumed to be the vapour pressure at the liquid temperature), p is the pressure in the liquid surrounding the bubble, ρ_f is the liquid density, and σ is the surface tension coefficient between the liquid and vapour. Note that this is derived from a mechanical balance, assuming no thermal barriers to bubble growth. Neglecting the second order terms (which is appropriate for low oscillation frequencies) and the surface tension, this equation reduces to:

$$\frac{dR_B}{dt} = \sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{4.2}$$

The rate of change of bubble volume follows as:

$$\frac{dV_B}{dt} = \frac{d}{dt}\left(\frac{4}{3}\pi v R_B^3\right) = 4\pi R_B^2 \sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{4.3}$$

and the rate of change of bubble mass is:

$$\frac{dm_B}{dt} = \rho_g \frac{dV_B}{dt} = 4\pi R_B^2 \rho_g \sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{4.4}$$

If there are N_B bubbles per unit volume, the volume fraction r_g may be expressed as:

$$r_g = V_B N_B = \frac{4}{3}\pi R_B^3 N_B \tag{4.5}$$

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and the total interphase mass transfer rate per unit volume is:

$$\dot{m}_{fg} = N_B \frac{dm_B}{dt} = \frac{3r_g \rho_g}{R_B} \sqrt{\frac{2}{3} \frac{p_v - p}{\rho_f}} \tag{4.6}$$

This expression has been derived assuming bubble growth (vaporization). It can be generalized to include condensation as follows:

$$\dot{m}_{fg} = F \frac{3r_g \rho_g}{R_B} \sqrt{\frac{2}{3} \frac{|p_v - p|}{\rho_f}} \operatorname{sgn}(p_v - p) \tag{4.7}$$

where F is an empirical factor that may differ for condensation and vaporization, designed to account for the fact that they may occur at different rates (condensation is usually much slower than vaporization).

Despite the fact that the previous equations have been generalized for vaporization and condensation, it requires further modification in the case of vaporization.

Vaporization is initiated at nucleation sites (most commonly non-condensable gases). As the vapour volume fraction increases, the nucleation site density must decrease accordingly, since there is less liquid. For vaporization, r_g is replaced by $r_{nuc}(1 - r_g)$ to give:

$$\dot{m}_{fg} = F \frac{3r_{nuc}(1 - r_g)\rho_g}{R_B} \sqrt{\frac{2}{3} \frac{|p_v - p|}{\rho_f}} \operatorname{sgn}(p_v - p) \tag{4.8}$$

where r_{nuc} is the volume fraction of the nucleation sites. The source equation is maintained in the case of condensation. It is important to note that in this model R_B represents the radius of the nucleation sites.

To obtain an interphase mass transfer rate, further assumptions regarding the bubble concentration and radius are required. The Rayleigh-Plesset cavitation model implemented in ANSYS CFX uses the following defaults for the model parameters:

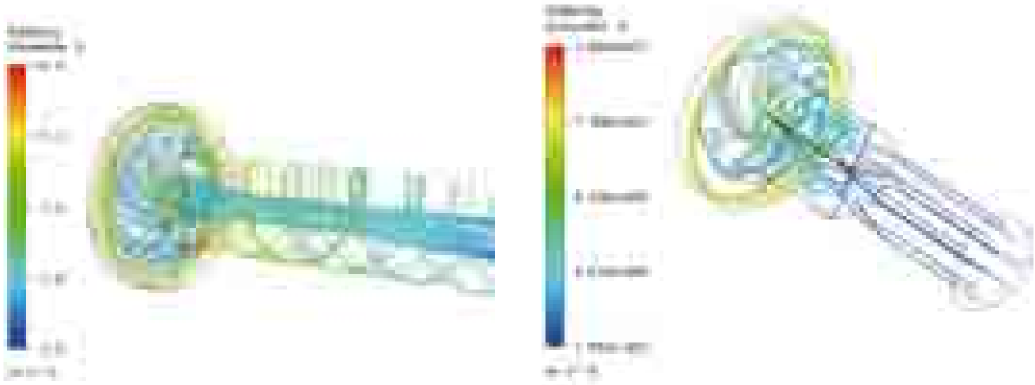
$R_B = 1\,\mu\text{m}$, $r_{nuc} = 5 \times 10^{-4}$, $F_{vap} = 50$, $F_{cond} = 0.01$.

4.1 CFD results

The present chapter includes results comparisons for both inlet pipe geometries (with and without guiding device). Diagrams and photographs show the same operating regime regarding relative pressure in the water reservoir (NPSH value) and convection term (flowrate) height. The influence of geometry on cavitation swirl has been analysed with stress laid on two-phase area propagation.

Since we have to model a change in a reference frame between the rotating domain (impeller) and stationary domain (pipe), the transient fluid-fluid interface has been defined.

Figure 8 shows operating regime pattern for system operating out of design point – with reduced flowrate for both geometries.



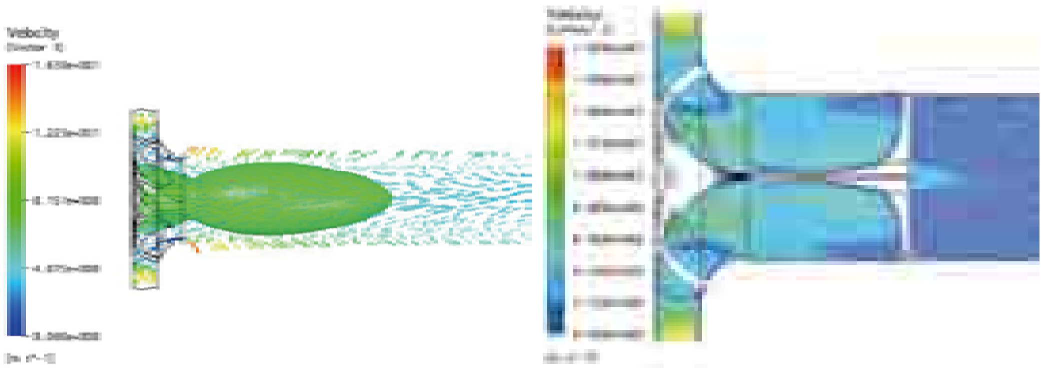
a) **b)**

***Figure 10**: Operating regime visualization using streamlines plots for both analysed geometries.*

A strong pre-rotating motion [5] in the inlet pipe especially near pipe walls is evident from Figure 10 (a) showing the case of geometry without a guiding device.

Comparing to the streamlines plot at Figure 10 (b) it could be concluded that the guiding device stops general swirling flow and splits it into four smaller flow channels where smaller swirls occur.

Figure 11 shows the unstable cavitating operating regime with a strong recirculating cloud of vapour bubbles at the inlet pipe walls connected to cavitation number decrease.



a) **b)**

***Figure 11**: Unstable cavitating pump operating regime.*

Strong recirculatory motion with an active flow area in the middle of the pump is shown in the picture showing geometry without guiding device (a). It is obvious from water vapour isosurface that cavitation swirl takes place in the low pressure region of the active flow area.

A split recirculation cloud is evident from Figure 11 (b) showing an operating regime with a guiding device. It is evident that the cavitation cloud remains in the guiding device channels.

Figure 12 and Figure 13 shows the cavitation visualization comparison at both geometries.

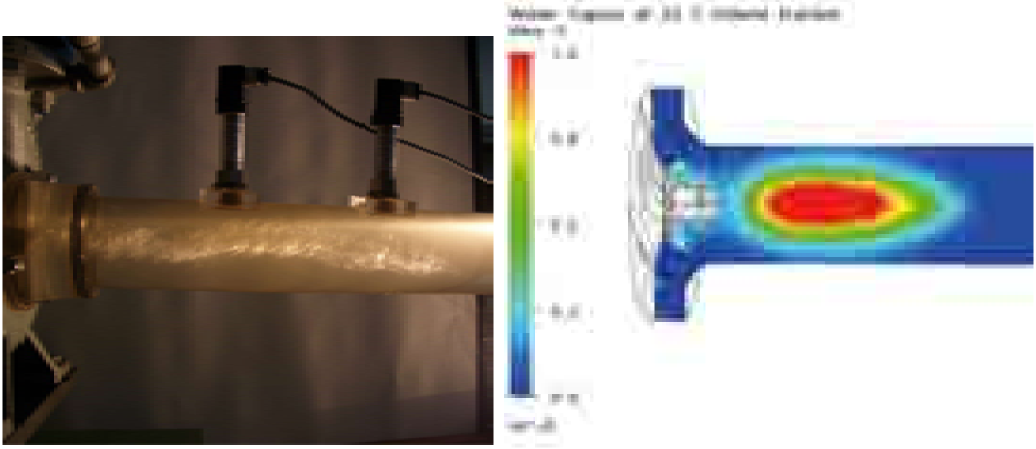


***Figure 12**: Hydro-dynamically induced cavitation surging on the inlet geometry without guiding device.*

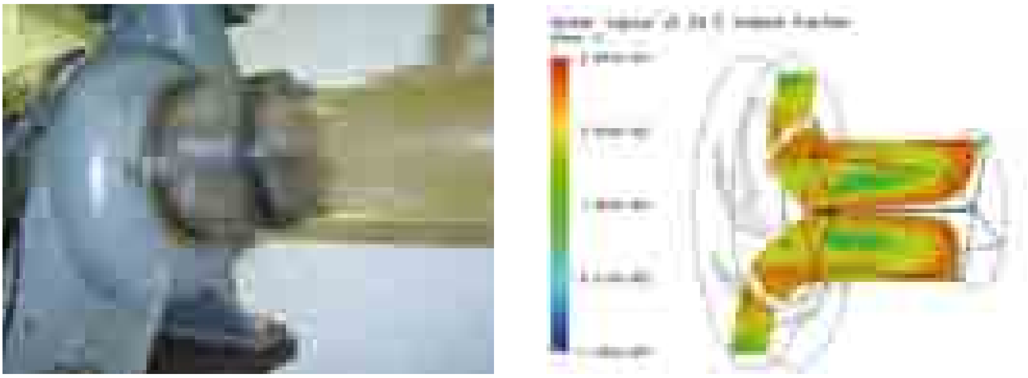


***Figure 13**: Hydro-dynamically induced cavitation surging on inlet geometry with guiding device.*

It can be concluded from Figures 12 and 13 that the guiding vanes split the rotating two-phase region into the four flow passages. It is also evident that the cavitation region becomes shorter.

Based on the good agreement evident in the photo comparing to CFD simulation results, it could be concluded that the homogenous cavitation transport model based on the Raleigh-Plesset equation (as an interphase mass transfer model) represents an effective tool for cavitation prediction in hydraulic machinery.

5 MATHEMATICAL MODELS FOR FREQUENCY ANALYSIS

Although computer performance has increased rapidly in recent years, we are still not able to perform full frequency analyses using computational fluid mechanics results. The reason for this could be found in the limitations of computer memory and calculation times.

Accordingly, multi-frequency instabilities of cavitating turbo-machinery parts (especially for multi-blade impellers) can be analyzed using different analytical models. Recent investigations of cavitating turbo-pump inducers [7] has revealed the existence of more complex instabilities than previously recognised cavitation surge and rotating cavitation. These multi-frequency instabilities were not under the scope of the present study and can also be found in relevant literature [5] and [8].

6 CONCLUSIONS

Hydro-dynamically induced surge is a type of system instability that involves not just the pump characteristics but those of the complete piping system in a complicated unstable operating regime. The present contribution presents the experimental and numerical analyses approach. The results show that use of the simple guiding device results in dominant pressure pulsations and a decrease of the cavitation region.

It is evident from the experimental analysis that dominant frequencies scale with the impeller rotating speeds, where some of them show large independence from the impeller rotation frequency at both inlet pipe geometries.

The homogenous mathematical model for cavitation is a suitable tool for the prediction of cavitation in turbo machinery and a fast method for geometry influence analysis.

The computational fluid mechanics results show that the cavitation region transition from the area of impeller channels in the entrance pipe is connected to recirculation flow and with decreased active flow area in the intake pipe.

The swirl length is based on the geometry of the pump entrance area and pressure in the reservoir, which defines the volume fraction of the gas phase and the cavitation swirl diameter.

A simple guiding device splits the pre-rotating flow motion into four disconnected flow channels resulting in increased operating characteristics and possible operating complications connected with pressure pulsations and a decrease in vibrations.

Owing to transient nature of complicated turbulent two-phase flow regime in the analysed system, both numerical and experimental research methods should be used.

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Notations

R_B	bubble radius,
p_v	pressure in the bubble,
p	pressure in the surrounding liquid,
ρ_f	liquid density,
ρ_g	vapour density,
σ	surface tension between the liquid and vapour,
V_B	bubble volume,
m_B	bubble mass,
t	time,
N_B	bubble number density,
r_g	volume fraction,
$\dot{m}_{fg}$	interphase mass transfer per unit volume,
F	empirical factor,
r_{nuc}	volume fraction of nucleation sites

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)

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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.

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

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1 MAIN CHAPTER

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

1.1 Section

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1.1.1 Sub-section

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

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$$c = \sqrt{a^2 + b^2} \tag{1.1}$$

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