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Jurij AVSEC
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COGENERATION AND TRIGENERATION SYSTEMS

KOGENERACIJSKI IN TRIGENERACIJSKI SISTEMI

Simon Marčič[ℜ]

Keywords: cogeneration, trigeneration, woodgas

Abstract

This paper describes a cogeneration plant using wood biomass as fuel. Forests cover 56% of the surface area in Slovenia, providing plenty of waste wood to be used as an energy source. Waste wood unsuitable for the lumber industry is ground into biomass of G50 size, which are chips of, measuring on average 3–5 cm and up to 8 cm. Biomass is dried in a drier to reduce its moisture content to 15%. Wood biomass gasification takes place in a gasifier. Carbon monoxide and hydrogen, gasification end products, are used as fuels for a boiler and two gas engines. The boiler heat is used for wood-drying purposes. The cogeneration plant uses a 1 MW Caterpillar generator set and a 0.45 MW MAN generator set. Cooling water waste heat of both gas engines and exhaust gases are used for heating the wood drier and the nearby residential area.

Povzetek

V članku je opisana kogeneracija, ki uporablja za gorivo lesno biomaso. Slovenija je dežela, katere površina je 56% pokrita z gozdovi zato ima veliko odpadnega lesa, ki se lahko uporablja kot gorivo. Odpaden les, ki je za industrijsko rabo neuporaben zmeljemo v biomaso granulacije G50. To so sekanci velikosti do 8cm, ki v povprečju merijo od 3-5cm. Biomasa se posuši v sušilcu na vlažnost do 15%. V uplinjevalcu se lesna biomasa uplini. Končni produkt uplinjevanja je ogljikov monoksid in vodik, ki se uporabljata kot gorivo za kotel in plinska motorja. Toplota kotla se uporablja za sušenje lesa. Kogeneracija ima en Caterpillar genset moči 1 MW in MAN genset moči 0,45 MW. Odpadno toploto hladilne vode obeh plinskih motorjev in izpušnih plinov uporabimo za ogrevanje sušilnice lesa in bližnje stanovanjsko naselje.

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1 INTRODUCTION

The demand for thermal and electrical energy is typically met by supplying power from the local distributor's network and generating heat by burning fuel in a furnace or a boiler. Cogeneration technology, however, provides significant fuel saving and reduction in the emissions of harmful substances into the environment. Cogeneration or combined heat and power (CHP), [1], is the concurrent production of two or more types of useful energy from a single primary energy source. The two most frequently used forms are mechanical energy, used for powering an electric generator, and thermal energy used for heating or for the technological requirements of production in the pharmaceutical and other industries. Trigeneration differs from cogeneration in that waste heat is used for both heating and cooling, typically in an absorption refrigerator, [2, 3].

Large amounts of heat are released into the atmosphere via steam condensers and cooling towers during the operation of conventional power plants. In cogeneration systems using internal combustion engines, however, the waste heat of engines and exhaust gases may be exploited. Most of such thermal energy can be used to meet the demand for heat. The efficiency of a conventional power plant, ranging between 30% and 40%, is increased to 80%-90% efficiency in a cogeneration system.

For the production of mechanical energy that drives an electric generator, gas turbines are usually used for power levels over 5 MW, while for lower levels a diesel or spark ignition engine is used. Diesel engines are used with diesel fuel or biofuel, [4, 5]. A spark ignition engine is used in the case of natural gas, [6]. Another variant is the wood gasifier CHP plant in which wood pellets or wood chip biofuel is gasified in a zero oxygen, high temperature environment; the resulting gas is then used to power the gas engine.

In Slovenia, approximately 2% of electricity is generated using cogeneration systems. Industrial and district heating networks ensure the growth of such technology. Today, many existing systems are outdated, providing myriad opportunities for reconstruction. One concept for the development of households and industry envisages the construction of several small biomass units and the application of natural gas as a fuel with a relatively extensive distribution network. This concept has good development potential in Slovenia [7]. Forests cover 56% of the surface area in Slovenia, which has, as a result, a lot of waste wood to be turned into biomass. Biomass is an important fuel in Slovenia. Biomass is gasified in a gasifier, and the wood gas obtained is used to power the gas engine.

The most efficient example of the use of biomass is the energy plant in Güssing, Burgenland, Austria, where the total energy demand of the village is met by biomass. Significant power plants include a 2 MW electric power 4.5 MW thermic wood gas generator power plant in Güssing and in nearby Strem, a 0.5 MW electric power 0.5 MW thermic biomass gasification power plant using green silage re-growing raw materials, such as grass, clover, maize and sunflower [13].

This paper describes a biomass cogeneration system as the first of this type in Slovenia (Fig. 1), located in Ruše.

2 DESCRIPTION OF A WOOD BIOMASS COGENERATION

Waste wood ground into biomass is used as input fuel. The schematic diagram of a wood CHP plant and the fuel flow are shown in Fig. 2. Wood gas, generated in a gasifier, is used as a fuel for the boiler, producing heat for the wood-drying facility. Most of the wood gas is used for powering the Caterpillar and MAN gas engines. The former drives the $1MW_{e,}$ and the latter the $450kW_e$ electric generator. The electricity thus generated is sold to the Slovenian power grid at a price of EUR 0.27/kWh, with the Slovenian government subsidising energy-related facilities with total efficiency exceeding 80%. The generated heat of engine exhaust gases, cooling water, and heat from intercoolers is used for the wood-drying facility and the heating of a nearby residential area. The heat is sold at a price of EUR 0.02/kWh.

***Figure 1**: Cogeneration plant*

3 DRIER

Waste wood unsuitable for lumber industry is in the form of stem wood. The wood has the following composition: 40–50% cellulose, 20–30% lignin, and 20–30% components such as carbohydrates, fats, tannin and minerals.

It is first dried in the open air and then transported by means of a forklift truck to a grinder mill, where it is ground to G50 biomass, i.e. 8 cm chips, mostly measuring 3-5 cm. Subsequently, the biomass is transported to a weekly storage container. It serves as a reservoir with a system that spreads the biomass evenly over the entire storage surface. At its bottom, the container is fitted with a system of movable rods, moving the biomass, by means of a hydraulic pump, towards the

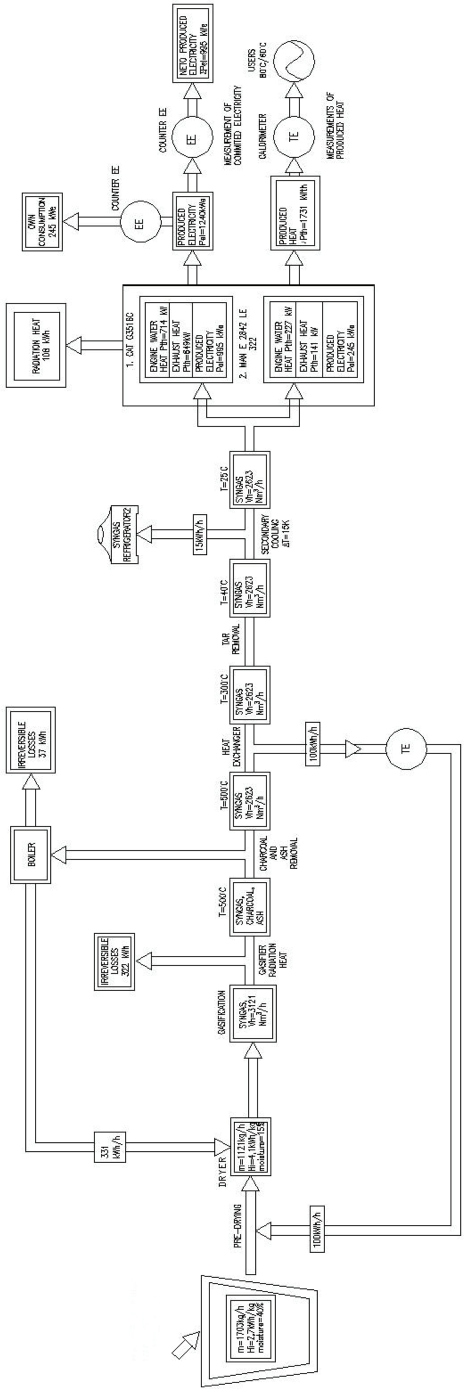

***Figure 2**: Diagram of the plant and the fuel flow*

outlet from the weekly storage container, where the biomass is discharged onto a conveyer belt. From there, the biomass is fed into a screening machine, where it is divided into three parts: the smallest are used for the biomass boiler and transported by the conveyer belt into the storage container, while the oversized ones are reground. The G50 biomass is transported via the screening-storage container conveyer belt into the biomass storage area. The lower heating value (LHV) of this biomass is 2.7 kWh/kg and its moisture content 40%. The biomass is transported from here into a drier for pre-drying. The heat for biomass drying is partly provided by the boiler and partly by the heat exchanger, cooling the wood gas from 500 °C to 300 °C (Fig. 2). The biomass is dried to 15% of moisture content in the drier, and its lower heating value (LHV) increases to 4.1 kWh/kg. The chemical composition of such biomass is 50% carbon, 42% oxygen, 6% hydrogen, 1% methane, 1% nitrogen and minerals. The wood biomass is fed from the drier, where pre-drying takes place, into the gasifier.

4 GASIFICATION AND WOOD GAS PREPARATION SYSTEM

A gasifier is the device in which sawdust and G50 chip gasification process takes place. The cylindrical gasifier is a downdraft unit, which means that the wood biomass and wood gas flow in the same direction, i.e. from the top to the bottom. The biomass in the form of wood chips is fed by means of conveyer belts and an elevator into a dispenser with double pneumatic flaps. From the dispenser, it enters the upper part of the gasifier via a longitudinal fixed grid.

Wood biomass gasification involves five phases [8, 9]:

1. Biomass drying phase takes place in the drying zone, where biomass is dried at temperatures from 100 °C to 150 °C. Moisture in the biomass evaporates and in the reduction zone it reacts with carbon to form hydrogen and carbon monoxide.

2. Pyrolysis of the dried biomass takes place in the pyrolysis zone at temperatures from 200 °C to 500 °C. Pyrolysis is the application of heat to biomass, in an absence of air, in order to break the biomass down into charcoal and various tar gasses and liquids. It is essentially the process of charring. The biomass breaks down into solids, liquids and gases at temperatures of over 250 °C. The solids that remain are charcoal. The gases and liquids that are produced are collectively called tars.

3. The heat needed for drying, pyrolysis and reduction is obtained through combustion in the combustion zone. Tar gases and charcoal from pyrolysis are used as a fuel. The necessary amount of air for combustion is blown into the combustion zone through nozzles. The cracking of biomass also takes place in this zone. Large molecules, such as tar, break down into lighter gas molecules, whereby heat is intensely supplied. The tar gas break-down process is crucial for proper internal combustion engine operation. Heavy molecules of tar gases are condensed at a spark plug and at valves of the engine and cause engine malfunction. Combustion and cracking are running from 800 °C to 1200 °C. The carbon content in the biomass is the highest and, therefore, the basic reaction in the combustion zone is:

$$C + O \leftrightarrow CO_2 + 34\,\text{MJ/kgC} \tag{4.1}$$

4. Reduction in a gasifier is accomplished in the reduction zone by passing carbon dioxide or water vapour across a bed of red hot charcoal. The carbon in the hot charcoal is highly reactive with oxygen; it has such a high oxygen affinity that it strips the oxygen off water vapour and carbon dioxide, and redistributes it to as many single bond sites as possible. The oxygen is more attracted to the bond site on the carbon than to itself; thus, no free oxygen can survive in its usual diatomic O_2 form. All available oxygen will bond to available carbon sites as individual oxygen until all the oxygen is gone. The reduction reactions are

$$CO_2 + C \rightarrow 2CO \tag{4.2}$$

$$H_2O + C \rightarrow CO + H_2 \tag{4.3}$$

Through this process, carbon dioxide is reduced by carbon to produce two carbon monoxide molecules, and H_2O is reduced by carbon to produce H_2 and carbon monoxide. Carbon monoxide and hydrogen are end products of a gasifier and used as a fuel for the boiler and both gas engines. The gasifier capacity is 2623 Sm³ of wood gas per hour. The temperature of the gas at the outlet from the gasifier is 500 °C. The gasifier waste heat flow is 322 kW.

A reactor retains charcoal to reduce some wood gas components due to a higher heating value (LHC), while it allows the ash at the bottom of the gasifier to be discharged. The gasifier is fitted with a grid at the bottom, through which fuel dosing takes place. The gasifier is insulated by a thick layer of thermal concrete and fitted with connections for the lateral air inlet and outlet of gasification products towards the boiler and the engine. Syngas thus generated is too hot and too dirty to enter the internal combustion engines; as a result, it requires adequate prior treatment.

A portion of the gas is fed to the boiler (Fig. 2), generating heat for biomass drying. The gas outlet heat power is 368 kW. The remaining amount of gas (2623 Nm³) enters the gas-water tubular heat exchanger where it is cooled down from 500 °C to 300 °C. The heat exchanger thermal capacity is 100 kW and is used for biomass pre-drying (Fig. 2). Gas is fed from the heat exchanger to a tar removal device. Tar has to be removed from gas as it causes coking at engine spark plugs and plugging of the wood gas-air mixing valve nozzles. After 1200 hours of engine operation, traces of tar and tar combustion products were observed on the engine valves. Wood gas then enters the tubular heat exchanger, where it is cooled down to 40 ^{0}C (Fig. 2). This heat is lost in the process; heat losses amount to 344 kW. The gas then enters the dust remover and a series of fine filters. During cogeneration, the filters are replaced on a weekly basis. The filtered gas enters a wood gas cooler 2, where it is cooled down to 25 °C. Gas cooling takes place in the water-wood gas heat exchanger. Afterwards, the filtered and cooled down gas enters the gas engines.

5 GENERATOR SET

Cogeneration has two generator sets, a Caterpillar G CAT 3516C with mechanical power of 1030 kW and electric power of 995 kW and an ER MAN E 2842 LE 322/LSA 47.2 S5 with mechanical power of 270 kW and electric power of 245 kW (Fig. 2).

The Caterpillar ER CAT 3516C engine exhaust gas flow rate is 7254 kg/h and outlet temperature 394 °C. The gases are cooled down to 120 °C in the tubular heat exchanger. The heat exchanger thermal capacity is 649 kW.

The engine is water cooled. The cooling water flow rate is 42 m^3/h; cooling water also cools the engine oil. The cooling system outlet water temperature is 90 °C and the inlet temperature 70 °C. The cooling water heat is transformed in a plate heat exchanger into the wood cooling facility heat. The heat exchanger thermal capacity is 694 kW.

The wood gas-air mixture is cooled down in the intercooler from 80 °C to 40 °C and additional 20 kW of thermal power is obtained. The total thermal power of the engine cooling water and the mixture cooling is 714 kW.

The intercooler cooling water flow rate is 20 m^3/h.

The total thermal power of the Caterpillar G CAT 3516C generator set is 1363 kW and its total efficiency 83%.

The electric generator efficiency is 96.7 %, cos f=0.9.

According to the available information, this is the first Caterpillar generation set application using wood gas.

The ER MAN E 2842 LE 322/LSA 47.2 S5 engine exhaust gas mass flow rate is 1302 kg/s, with the outlet temperature of 440 °C. Exhaust gases are cooled down to 120 °C in the tubular heat exchanger. The heat exchanger thermal power is 141 kW.

The engine is water cooled. The cooling water flow rate is 15.2 m^3/h; cooling water also cools the engine oil. The cooling system outlet water temperature is 90 °C and the inlet temperature 70 °C. The cooling water heat is transformed in a plate heat exchanger into the wood cooling facility heat. The heat exchanger thermal capacity is 227 kW.

The total thermal power of the ER MAN E 2842 LE 322/LSA 47.2 S5 generator set is 368 kW.

The efficiency of the Leroy Sommer LSA 47.2 S5 electric generator is 93.8%, cos f=0.8.

The generator set total efficiency is 82%.

The total electric power of both generator sets is 1240 kW, and the total thermal power used for heating the drier is 1731 kW.

The outlet water temperature for the wood drier or heating is 80 °C, the inlet temperature is 60 °C, and the mass flow rate 20.6 kg/s.

6 ECONOMIC ANALYSIS OF COGENERATION

The wood biomass cogeneration investment costs totalled €6 million [10, 11, 12]. Out of the total electric power of 1240 kW, 245 kW of power is used for own consumption and 995 kW sold into the Slovenian power grid at a price of EUR 0.27/kWh, subsidised by the Slovenian government. Heat is fully sold at a price of €0.02/kWh. The electricity sold generates the highest revenue. The cogeneration plant operates at full capacity 80% of time in a year or 8760 hours per year or 7008 hours of operation. The revenue from the sold electricity is

7008 hours × 995 kW × €0.27/kWh = €1,882,699.20.

The revenue from the heat sold is

7008 hours × 1731 kW × €0.02/kWh = €242,616.96.

The total revenue is

€242,616.96 + €1,882,699.2 = €2,125,316.16.

The annual operating costs are estimated at 2% of the value of investment or €120,000.

The cogeneration plant employs eight people. The costs of their salaries and personal equipment needed for the maintenance of the facility amount to €200,000 per year.

The primary energy consumption of both cogeneration engines at 82% efficiency is

$$\left(P_{el}+P_{heat}\right)/h=(1240kW+1731kW)/0.82=2971kW/0.82=3623kW. \tag{6.1}$$

The biomass consumption of both engines by taking into consideration the below indicated biomass lower heating value (LHC) of 2.7 kWh/kg and 40% moisture content is

$$\dot{m}=\frac{P_{tot}}{H_i}=\frac{3623}{2.7\cdot 3600}=0.372\frac{kg}{s}=1431kg/h \tag{6.2}$$

The overall consumption of the system of both engines and the boiler, generating the heat for biomass drying and pre-drying and for covering the losses is 1703 kg/h of biomass. The yearly consumption of biomass at 7008 operating hours is 11,934,624 kg. The annual biomass cost at the price of €0.05/kg is €596,731.2.

The total efficiency of the entire plant when the consumption of heat for wood drying and pre-drying is taken into account and for powering other auxiliary units is

$$\frac{P_{el}+P_{heat}}{H_i\cdot\dot{m}}=\frac{1240+1731}{2.7\cdot 3600\cdot 0.473}=0.646 \tag{6.3}$$

The operating costs, costs of employee salaries and of their equipment and the wood biomass price are

€200,000 + €120,000 + €596,731.2 = €916,731.2.

The cogeneration net annual revenue amounts to

€2,125,316.16 – €916,731.2 = €1,208,584.96.

The investment in cogeneration is repaid in

$$\frac{6,000,000}{1,408,58496} = 4.96 \text{ years}$$

7 DISCUSSION

This paper describes a cogeneration plant for the production of electricity and heat used in a wood drying facility. The heat may also be used for heating in a nearby residential area. Waste wood, in particular stem wood unsuitable for industrial applications, is the fuel. The cogeneration plant described in this paper is the first in Slovenia and one of the first in the world in the power range of up to 1.5 MW, operating on biomass.

Waste wood comprising 40–50% cellulose, 20–30% lignin, and 20–30% components such as carbohydrates, fats, tannin and minerals is first dried in the open air and then transported into a grinder mill where it is ground to G50 biomass, i.e. wooden chips with the size of up to 8 cm. The lower heating value (LHC) of the biomass is 2.7 kWh/kg and its moisture content 40%. Biomass is dried in the drier to a moisture content of 15% prior to entering the gasifier to increase its LHC to 4.1 kWh/kg. The biomass prepared in this fashion has the following chemical composition: 50% carbon, 42% oxygen, 6% hydrogen, 1% methane, and 1% nitrogen and minerals.

The gasifier is of a downdraft model and produces 3121 Nm^3 of wood gas per hour, containing carbon monoxide and hydrogen as the burning substance. The two gas engines consume 2623 Nm^3 and the rest the boiler generating heat for wood drying.

Electricity is generated by two generator sets: a Caterpillar G CAT 3516C (995 kW electric power, 1363 kW thermal power, 83% total efficiency), and an ER MAN E 2842 LE 322/LSA 47.2 S5 (245 kW electric power (Fig. 2), 368 kW thermal power, 82% total efficiency). The cogeneration system consumes 245 kW of power for its own use.

The generated power is sold to the Slovenian power distribution grid at a price of €0.27/kWh, subsidised by the Slovenian government. Heat is fully consumed in the wood drier. The price of the heat sold is low at only €0.02/kWh. Technically speaking, the sale of heat for sanitary water heating and heating of the nearby residential area is also possible. Unfortunately, heat for district heating purposes can only be sold in winter.

The total efficiency of the facility is 64.6% and the investment is to be repaid in five years.

References

[1] **Z.G. Sun, R.Z. Wang, W.Z. Sun:** *Energetic efficiency of a gas engine-driven cooling and heating system,* Applied Thermal Engineering, 24 (5–6) (2004), pp. 941–947

[2] **V. Havelský***: Energetic efficiency of cogeneration systems for combined heat, cold and power production,* International Journal of Refrigeration, Elsevier, Volume 22, Issue 6, September 1999, Pages 479–485

[3] **P.E. Hufford***: Absorption chillers improve cogeneration energy efficiency*, ASHRAE J. March, 1992, pp. 46–53

[4] **Z. Husain, , Z.A. Zainal, M.Z. Abdullah**: *Analysis of biomass-residue-based cogeneration system in palm oil mills*, Biomass and Bioenergy, Volume 24, Issue 2, February 2003, Pages 117–124

[5] **D.O. Hall, G.W. Barnard, P.A. Moss***: Biomass for Energy in the Developing Countries*, Pergamon Press, Oxford, 1982

[6] **P. Chester**: *Gas as a fuel source in CHP systems*, Energy World (Aug., 12–15 1989).

[7] **I. Zakaria**: *Renewable energy program from national perspective*, Renewable Energy Power (SREP) Program for Palm Oil Industry, 2002

[8] **Greenhouse Gas Technology Center,** *Technology Assessment Report*: Aqueous Sludge Gasification Technologies, EPA/600/R-12/540, Version 1.5, 2012

[9] **D.A. Tillman, A.J. Rossi, W.D. Kitto**: *Wood Combution*: Principles, Processes and Economics, Academic Press, New York, 1981

[10] **J.L. Silveira, A. Beyene, E.M. Leal, J.A. Santana, D. Okada***: Thermoeconomic analysis of a cogeneration system of university campus*, Applied Thermal Engineering, 22 (13) (2002), pp. 1471–1483

[11] **G. Sunberg, D. Henning***: Investments in combined heat and power plants: influence of fuel price on cost minimized operation,* Energy Conversion and Management, 43 (5) (2002), pp. 639–650

[12] **C.F. Lin, D.H. Lu**: *Feasibility analysis of cogeneration and combined heat, power and cold for Tulufan city,* Gas & Heat, 20 (4) (2000), pp. 303–304 (in Chinese)

[13] http://www.eeeinfo.net/cms/netautor/napro4/appl/na_professional/parse.php?mlay_id=2500&mdoc_id=1000558

Nomenclature:

(symbols)	(symbol meaning)
H_i	lower heating value (LHC) [J/kg, kWh/kg]
P_{el}	electrical power [W, kW]
P_{heat}	thermal power [W, kW]
$\dot{m}$	mass flow [kg/s]
P_t	total power [W, kW]

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AN OVERVIEW OF THE EXPLOITATION OF STEAM IN THE SECONDARY SYSTEMS OF NPP KRŠKO

PREGLED SISTEMOV ZA ODJEM PARE V SEKUNDARNEM KROGU NEK

Urška Novosel[ℜ], Matjaž Žvar, Tomaž Ploj, Jurij Avsec

Keywords: nuclear power plant, steam exploitation, thermodynamic analysis, district heating

Abstract

Nuclear energy is used to produce electricity; it can also be applied in a cogeneration process to produce power and heat. Nuclear energy is a very clean source as it produces almost no greenhouse gases, such as CO_2. Under the Kyoto Protocol, the signatory countries committed themselves to reducing CO_2 emissions; therefore, it is reasonable to take advantage of existing nuclear facilities to the greatest extent possible. This means that even though they were built only to produce electricity (Krško NPP, for example), they can also be used for other applications: a source of heat for district heating or desalination of sea water in areas at risk of a lack of drinking water. Nevertheless, the technology can be upgraded by using the experience of other nuclear power plants (NPPs) having similar district-heating systems.

In this paper, the focus was on models of steam consumption from the secondary system of the Krško NPP for the Krško and Brežice district-heating purposes. The Krško NPP has a Westinghouse PWR with 2,000 MWt and an electrical power output of 696 MW to the grid. The technological part is divided into three main systems: primary, secondary and tertiary. The first two are sealed and isolated from the environment while the third, which uses water from the River Sava for cooling, is connected to the outside environment. This paper focuses on the technical solution to obtain heat from the NPP's secondary system for district-heating purposes. According to thermodynamic calculations, the secondary system determines the reduction of produced electricity, when the

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steam is exploited in front of the turbine. This paper presents some technical, economic and safety solutions for the highly efficient extraction of vapour for district heating. Furthermore, some thermodynamic calculations and technical solutions for district-heating purposes using the Krško NPP for the Krško-Brežice area are shown.

Povzetek

Nuklearna energija se v svetu izkorišča za proizvodnjo električne energije, kot tudi za kogeneracijo – torej proizvodnjo električne energije in toplote. Velja za čisti vir energije, saj v procesu ne nastajajo toplogredni plini, predvsem CO_2. Po Kjotskem protokolu so države podpisnice zavezane k zmanjšanju izpustov CO_2, torej bi bilo smiselno obstoječe jedrske objekte izkoristiti v največji mogoči meri. To pomeni, da bi jih tam, kjer so namenjeni samo za proizvodnjo električne energije (kot NEK), uporabili tudi za druge aplikacije, kot je izkoriščanje toplote v namen daljinskega ogrevanja ali razsoljevanja morske vode na območjih, kjer so velike možnosti za pomanjkanje oskrbe s pitno vodo. Pri tem si lahko pomagamo z izkušnjami iz ostalih nuklearnih elektrarn, ki že imajo podobne sisteme za kogeneracijo.

V našem primeru se bomo osredotočili na odjem pare iz sekundarnega kroga NEK za sistem daljinskega ogrevanja Krškega in Brežic. NEK ima Westinghouseov PWR z 2000 MWt in z močjo na pragu 696 MW. Tehnološki del je razdeljen na primarni, sekundarni in terciarni krog, prva dva sta sklenjena in nimata stika z okoljem, tretji pa je povezan z okoljem, saj uporablja vodo iz Save za hlajenje. V članku je poudarek na tehnični rešitvi pridobivanja toplote iz sekundarnega kroga NEK za sistem daljinskega ogrevanja. Po termodinamične izračunu lahko določimo, koliko bi se zmanjšala proizvedena električna energija, saj bi paro odjemali pred turbino. V članku so predstavljene nekatere tehnične, ekonomske in varnostne rešitve za čim bolj učinkovito odjemanje pare za daljinsko ogrevanje. Nadalje so prikazani termodinamični izračuni in tehnične rešitve za sistem daljinskega ogrevanja s pomočjo NEK za območje Krškega in Brežic.

1 INTRODUCTION

This paper aims to present the reapplication of waste heat generated in electricity production at the Krško NPP. One of the reapplication options is the use of waste heat from the NPP for the heating of the towns of Krško and Brežice.

Heating plants, nuclear power plants, and thermoelectric power plants are industrial facilities generating not only inexpensive electrical energy but also very inexpensive steam. It is known that nuclear power plants produce electricity at considerably lower costs than heating and thermoelectric power plants. The indicators in terms of electric energy prices are even more favourable if nuclear energy is compared to other renewable sources of energy, such as photovoltaic power plants. Nuclear power is important for the production of very large amounts of cheap energy, both electricity and heat. In addition to its economic effects, nuclear energy also provides an option for the use of sustainable sources and the way towards a carbon-free society. Environmental problems such as rising levels of carbon dioxide in the atmosphere are deeply troubling issues. Nuclear power plant technology, including its safety, is constantly progressing and has achieved very high level. New types of reactors (fusion reactors) will allow an even more efficient use of nuclear fuel in the near and distant future. The efficiency of the use of nuclear reactors can be further improved by their upgrading for heating and cooling purposes.

District heating and cooling is one of the possible solutions for optimising the operations of nuclear power plants. Examples of good practice are the nuclear power plants Bilibino in Russia and Beznau in Switzerland. In this article, we will attempt to find technical solutions and economic analysis for the PWR nuclear power plant in Krško.

2 KRŠKO NPP

The Krško NPP is a Westinghouse PWR plant with a power rating of 2,000 MWt, a net electrical output of up to 696 MWe and is connected to the 400 kV grid. It generates more than 5 TWh of electrical energy per year or over 40% of the electricity produced in Slovenia, [1]. The Krško NPP's major components are illustrated in Figure 1.

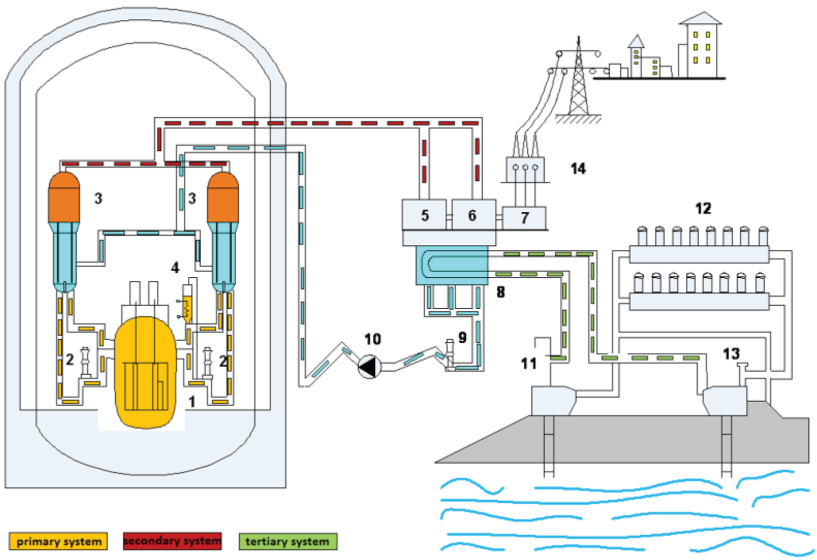

Figure 1: *NPP operating diagram [1]*

Key:

1	Reactor	8	Condenser
2	Reactor coolant pumps	9	Condensate pump
3	Steam generators	10	Feedwater pump
4	Pressurizer	11	Cooling Sava River water pump
5	High-pressure turbine	12	Cooling towers with cells
6	Low-pressure turbines	13	Cooling tower pump
7	Electric generator	14	Transformer

2.1 Description of the Secondary Systems in Krško NPP

This paper focuses on the NPP's secondary system that, in terms of thermodynamics, acts as a heat engine, similar to a conventional thermoelectric power plant.

Dry saturated steam generated in the steam generators enters the high-pressure turbine, where it expands to 9 bar, thus creating force. After expansion, steam becomes wet and it flows into the moisture separator and reheater where water drops are removed; saturated steam still remains to be reheated in reheaters. Such reheated steam expands in low-pressure turbines to a condenser pressure of 0.05 bar. The steam is condensed in the condenser and the condensate water is pumped by the condensate pumps to the main feedwater pumps returning the water to the steam generators, [2]. Figure 2 shows a simplified diagram of the secondary system.

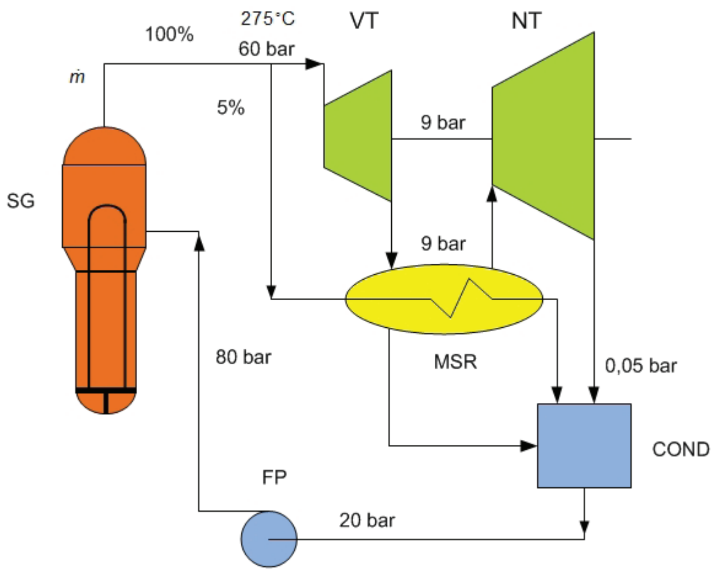

Figure 2: *Simplified diagram of the Krško NPP's secondary system*

Key to symbols used in Figure 2: SG – steam generator, VT ('HP') – high-pressure turbine, NT ('LP') – low-pressure turbine, MSR – moisture separator and reheater, COND – condenser, FP – feedwater pump.

Each element will be computed separately, i.e. VT (HP), followed by MSR, NT (LP) and finally FP. What happens to the enthalpy in each element will be determined, and the power output of the low-pressure turbine needed for any further computation purposes will be computed. A Mollier diagram and thermodynamic equations will be used, [2].

3 CALCULATION OF ENTHALPY FLOWS AND LOW-PRESSURE TURBINE POWER OUTPUT IN KRŠKO NPP

3.1 Introduction

The first law of thermodynamics will be used for the computation. Technical problems will be focussed on, as they are most relevant here; therefore, we begin with the following Equation (3.1):

$$\dot{Q}_{12} - \dot{W}_{12} = \dot{m}(h_2 - h_1) \tag{3.1}$$

In an adiabatic process Q = 0, and Equation (3.2) is developed to be used in the calculation.

$$(\dot{W}_{t12})_{ad} = \dot{m}(h_1 - h_2) \tag{3.2}$$

The data used for the calculation is taken from the Krško NPP's internal documents, [3].

3.2 Calculation of enthalpy flows and power outputs

3.2.1 High-pressure turbine

The processes in the high-pressure turbine in a Mollier diagram are illustrated in Figure 3.

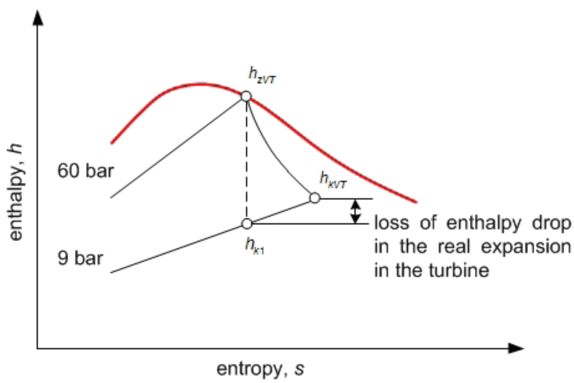

Figure 3: *Expansion in a high-pressure turbine in an h-s diagram*

The mass flow rate into the high-pressure turbine accounts for 95% of the total mass flow, which is why 0.95 is added to the right side of Equation (3.2) to calculate the turbine power output. The mass flow rate determined from the data is $\dot{m} = 1{,}088\,\frac{kg}{s}$. Furthermore, it is also taken into account that the expansion in the turbine is not isentropic but with efficiency $\eta_{VT} = 0.7879$. The unknown values are taken from the mechanical engineering handbook or a similar handbook, whereas the remaining values are calculated. Finally, the turbine power output is obtained using Equation (3.2):

$$\dot{W}_t = 0.95 \cdot 1{,}088 \cdot (2{,}785 - 2{,}517) \doteq \underline{277\text{MW}}$$

3.2.2 MSR

The MSR removes drops from the steam and reheats the steam. Figure 4 shows the process, including the reheating, in an h-s diagram. No turbine efficiencies are taken into account in the figure.

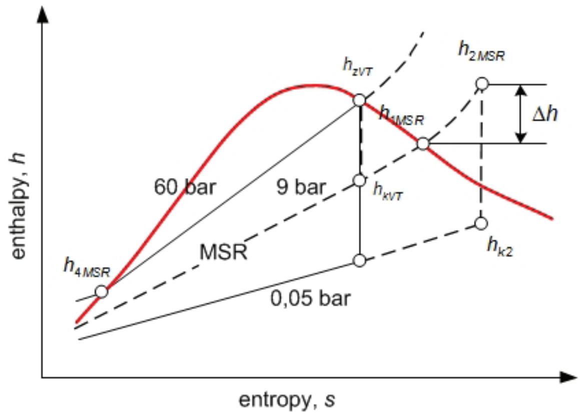

Figure 4: *Process including steam reheating in an h-s diagram*

First, the mass flow rates of steam and drops are calculated $903.4\frac{\text{kg}}{\text{s}}$, and $903.4\frac{\text{kg}}{\text{s}}$, respectively, and total mass flow $1{,}033.6\frac{\text{kg}}{\text{s}}$. From an energy balance in Equation (3.3), enthalpy growth Δh can be calculated using Equation (3.4), whereas other values are taken from the previous calculation or found in a mechanical engineering handbook, by taking into consideration the fact that the mass flow rate of fresh steam taken in front of the turbine accounts for 5% of the total mass flow rate. The basis for the overall calculation is the Mollier diagram for MSR shown in Figure 4. The value we are interested in is the initial state of steam at the entrance to the low-pressure turbine to be obtained from Equation (3.5).

$$x_{kVT} \cdot m_{VT} \cdot (h_{2MSR} - h_{1MSR}) = m_p \cdot (h_{zVT} - h_{4MSR}) \tag{3.3}$$

$$\Delta h = (h_{2MSR} - h_{1MSR}) = \frac{\dot{m}_p \cdot (h_{zVT} - h_{4MSR})}{x_{kVT} \cdot \dot{m}_{VT}} \tag{3.4}$$

$$h_{zNT} = h_{2MSR} = h_{1MSR} + \Delta h = 2{,}772 + 94.8 = 2{,}867\frac{\text{kJ}}{\text{kg}} \tag{3.5}$$

3.2.3 Low-pressure turbine

The calculation for the low-pressure turbine is the same as with the high-pressure turbine, but with different data. Figure 5 illustrates the processes in the turbine.

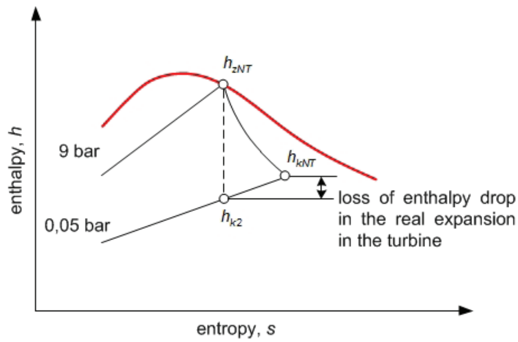

Figure 5: *Expansion in a low-pressure turbine in an h-s diagram*

Power output obtained in the calculation using Equation (3.6):

$$\dot{W}_t = 0.874 \cdot 1{,}033.6 \cdot (2{,}867 - 2{,}246) \doteq \underline{561\text{MW}} \tag{3.6}$$

3.2.4 Feedwater pump

Equation (3.7) is used to calculate the feedwater pump output, whereas the other data is available in Figure 2 or found using a mechanical engineering handbook. The actual feedwater pump output, taking into consideration a 50% efficiency, is shown in Equation (3.8).

$$\dot{W}_{FP1} = \dot{m}(p_1 - p_2) \cdot v \tag{3.7}$$

$$\dot{W}_{FP} = \frac{\dot{W}_{FP1}}{\eta_{FP}} = \frac{-7.7}{0.5} \doteq \underline{-15.4\text{MW}} \tag{3.8}$$

3.3 Computed values

Certain data from this section will also be used in the next one to see how much the power plant output (low-pressure turbine power output) would be lower, if the steam is used for district heating. The values indicated in this section are summarised in Table 1, [2].

Table 1: *Computed values*

	Designation (unit)	Value
High-pressure turbine power output	$\dot{W}_t$ (MW)	277
Quality of steam from high-pressure turbine	x_{kVT}	0.874
Low-pressure turbine power output	$\dot{W}_t$ (MW)	561
Quality of steam from low-pressure turbine	x_{kNT}	0.87
Feedwater pump output	$\dot{W}_{FP}$ (MW)	–15.4

4 EXTRACTION OF STEAM FOR KRŠKO AND BREŽICE DISTRICT-HEATING PURPOSES

4.1 Introduction

A heat exchanger would be installed behind the MSR and in front of the low-pressure turbine. Otherwise, all inlet and outlet flow rates should be calculated again, requiring a very expensive process, i.e. a new design of the system. Steam extraction in front of the low-pressure turbine is also the most cost effective. Another reason for steam extraction here is the relatively high level of steam temperature needed for district heating (at least 100° C). Figure 6 shows the heat exchanger location.

In order to meet the Krško and Brežice district-heating requirements, 80 MW of heat is needed. A calculation will be made for the amount of low-pressure turbine power output reduction in the case of a 10%, 20% or 30% heat loss. The results thus obtained will provide a basis for the comparison of heat and electricity prices.

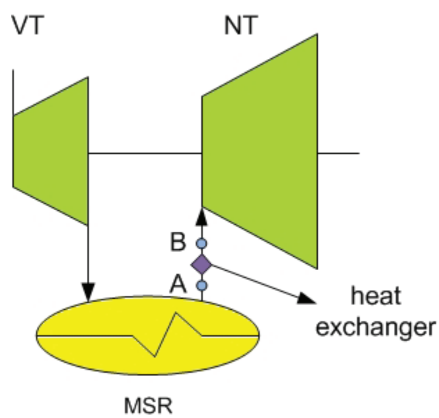

Figure 6: *Location of steam extraction or heat exchanger*

4.2 Calculation

As a result of steam extraction, enthalpy changes at the entrance to the low-pressure turbine, i.e. enthalpy in point B (Figure 6). This is the only parameter subject to change. It is to be calculated for each case separately (i.e. at various values of losses) using Equation (4.1).

$$\dot{Q} = \dot{m}_{NT} \cdot (h_A - h_B) \tag{4.1}$$

4.2.1 10 % loss

In this case, the required heat is $\dot{Q}_1 = 1.1 \cdot 80 = 88\text{MW}$, then, by using (4.1) we calculate h_B. This value is then put into Equation (4.2) and the turbine new power output is computed using Equation (4.3) and by how much the turbine power output has decreased, using Equation (4.4).

$$h_{kNT} = h_B - \eta_{NT} \cdot (h_B - h_{k2}) \tag{4.2}$$

$$\dot{W}_{t1} = 0.874 \cdot 1{,}033.6 \cdot (2{,}770 - 2{,}225) \doteq 492\text{MW} \tag{4.3}$$

$$\Delta P_1 = \dot{W}_t - \dot{W}_{t1} = 561 - 492 = 69\text{MW} \tag{4.4}$$

4.2.2 20 % loss

The calculation made is similar to the one above, yet with different values. The turbine power output is shown in Equation (4.5) as well as by how much the turbine power output has decreased in Equation (4.6).

$$Q_2 = 1.2 \cdot 80 = 96\text{MW}$$

$$\dot{W}_{t2} = 0.874 \cdot 1{,}033.6 \cdot (2{,}761 - 2{,}223) \doteq 486\text{MW} \tag{4.5}$$

$$\Delta P_2 = \dot{W}_t - \dot{W}_{t2} = 561 - 486 = \underline{75\text{MW}} \tag{4.6}$$

4.2.3 30 % loss

The turbine power output is now in Equation (4.7) as well as by how much the turbine power output has decreased in Equation (4.8).

$$\dot{Q}_3 = 1.3 \cdot 80 = 104\text{MW}$$

$$\dot{W}_{t3} = 0.874 \cdot 1{,}033.6 \cdot (2{,}752 - 2{,}221) \doteq 480\text{MW} \tag{4.7}$$

$$\Delta P_3 = \dot{W}_t - \dot{W}_{t3} = 561 - 480 = \underline{81\text{MW}} \tag{4.8}$$

Figure 7 shows the ratio between the power plant output and the quantity of steam in the case of different values of losses in the district-heating system.

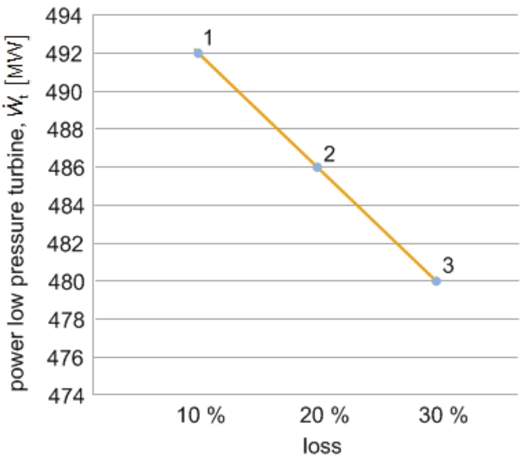

Figure 7: *Ratio between low-pressure turbine power output and the quantity of steam in the case of different values of losses in the district-heating system*

4.3 Computed values and comments

For each case separately, the minimum cost of 1 MWh of heat to compensate the cost of electricity from the NPP, which is €30 per 1 MWh, will be calculated, based on the assumption of a 24 h operation. The values are indicated in Table 2, [2].

Table 2: *Computed values*

No.	Losses in district heating (%)	Low-pressure turbine power output (MW)	Heat price (€/MWh)
1	10	492	25.9
2	20	486	28.1
3	30	480	30.4

The calculations showed that in view of the assumed heat losses, the price of 1 MWh of heat varies between € 25/MWh and € 31/MWh. This price can hardly be compared to the market prices, since many factors should have been taken into consideration, such as investment, amortisation period, CO_2 taxes, and others. No investment in the NPP was taken into consideration in the computation nor any investment in the distribution, nor any subsidies as there are no CO_2 emissions. However, the comparison was made of the price of 1 MWh of electricity and 1 MWh of heat. It is not surprising that interest in combined heat and power (CHP) technologies is growing.

5 CONCLUSION

This paper deals with the use of waste heat from the NPP for Krško and Brežice district-heating purposes. This would result in an increased efficiency of the existing electric power facility. There is a great deal of heat wasted in the Krško NPP and it should be used in order to increase the efficiency of the plant. A district-heating system would contribute to a cleaner environment in the Krško and Brežice area and would provide a more reliable heat supply. Moreover, it would also provide a financially more favourable solution. This paper also presents an original concept and a computation of the indicative costs of the generated heat.

References

[1] *Krško Nuclear Power Plant,* retrieved from: http://www.nek.si/ (17 August 2012)

[2] **U. Novosel:** *Pregled sistemov za odjem pare v sekundarnem krogu jedrske elektrarne – diplomsko delo,* University of Maribor, Faculty of Energy Technology, Krško, 2011

[3] **M. Žvar, T. Skobe:** *Parni sistem,* NEK strokovno usposabljanje, Ljubljana, 2005

Nomenclature

NEK	Nuklearna elektrarna Krško
NPP	nuclear power plant
$\dot{Q}$	heat flow rate [J/s]
$\dot{W}$	power output [W]
$\dot{m}$	mass flow rate [kg/s]
h	specific enthalpy [J/kg]
η	efficiency
MSR	moisture separator and reheater
x	quality of steam
P	power [W]
CHP	power and heat cogeneration

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SYSTEM CONTROL IN CONDITIONS OF FUZZY DYNAMIC PROCESSES

UPRAVLJANJE SISTEMA V POGOJIH MEHKIH DINAMIČNIH PROCESOV

Janez Usenik[R]

Keywords: dynamic system, control, random process, fuzzy reasoning, neuro-fuzzy training

Abstract

In this article, a mathematical model of controlling the system in conditions of fuzzy processes is presented. Such a system can also be a power supply system. Analytical approaches that can be used to describe the mutual impact of output and stocks (additional capacities) on hierarchically distributed occurrence/usage/variation or demand already exist. We add dynamics to the system with the use of continuous and discrete dynamic processes, which are of a random (stochastic) form. The dynamic discrete model of control for this system is built with a system of difference equations, and the dynamic continuous model is built with a system of differential equations. These systems of equations can be solved with a one-part z-transform in discrete situations in with Laplace transform in the continuous systems. Fuzzy system control follows a continuous and discrete stochastic mathematical closed-loop model of control of stocks (additional capacities) in production systems. The fuzzy model is demonstrated with a numerical example.

Povzetek

V članku je predstavljeno upravljanja sistema v pogojih mehkih dinamičnih procesov. Takšen sistem je lahko tudi energetski sistem. Razviti so analitični pristopi, s katerimi opišemo medsebojni vpliv proizvodnje ter zalog (dodatnih kapacitet) na hierarhično porazdeljeno prostorsko dogajanje/porabo/spremembo oziroma povpraševanje. V sistem vpeljemo dinamiko, kar storimo z uporabo zveznih in diskretnih dinamičnih procesov, ki so zaradi zahteve po čim tesnejšem približku opisova-

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nja dejanskega sistema, slučajnostne (stohastične) narave. Dinamični diskretni model upravljanja takšnega sistema izgradimo s sistemom diferenčnih enačb, zvezni model pa opišemo s sistemom diferencialnih enačb. Za reševanje uporabimo enostrano z-transformacijo pri diskretnih sistemih in Laplaceovo transformacijo pri zveznih sistemih. Mehko upravljanje sistema izhaja iz zveznega in diskretnega slučajnostnega matematičnega modela upravljanja zalog v proizvodnem sistemu. V članku je prikazan mehki pristop, ki ga vpeljemo z uporabo dvofaznega sistema mehkega sklepanja in pomeni približek zaprtozančnemu sistemu upravljanja. Mehki algoritem je ilustriran z numeričnim primerom.

1 INTRODUCTION

A production system (power supply, logistics, traffic, etc.) is a complex dynamic system. If we could create a theoretical mathematical dynamic model of it, we would have to take into consideration a great many variables and their interrelationships. However, with methods of logical and methodological decomposition, every system may be divided into a finite set of simpler subsystems, which are then studied and analysed separately, [1].

A model of optimal control is determined with a system, its input/output 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. In this article, dynamic systems will be studied. The optimality criterion is the standard against which the control quality is evaluated. The term 'control quality' means the optimal and synchronized balancing of planned and actual output functions, [2, 3].

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 either be a one-dimensional or multi-dimensional vector functions or they can be deterministic, stochastic or fuzzy. In this article, a system with fuzzy variables is presented.

2 DEFINING THE PROBLEM

Demand for a product 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 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 by stock. In the case of a power supplier, stock in the usual sense does not exist (such as cars or computers, etc.); energy cannot be produced in advance for a known customer, nor can stock be built up for unknown customers. The demand for energy services is neither uniform in time nor known in advance. It varies, has its ups (maxima) and downs (minima), and can only be met by installing and activating additional proper technological capacities. Because of this, the function of stock in the energy supply process is held by all the additional technological potential/capacities large enough to meet periods of extra demand. The demand for energy services is not given and precisely known in advance. Demand is not given with explicitly expressed mathematical functions; it is a random process for which the statistical indicators are known. The system input is the demand for the products/services that a given subject offers. 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 customers 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 sufficient, extra external purchasing 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 that will, according to given demand, provide basic information for the production process. In this way, the regulation circuit is closed. With optimal control, we will understand the situation in which all customers are satisfied with the minimum 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 difference equations for discrete systems or a system or differential equations for continuous systems, [2]. For this model, the regulation circuit is given in Figure 1, [4]. The task is to determine the optimum production and stock/capacities so that the total cost will be as low as possible, [3].

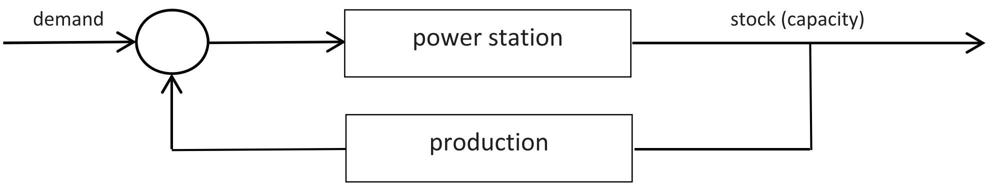

Figure1: *Regulation circuit of the power supply system*

3. A MATHEMATICAL MODEL OF THE SYSTEM CONTROL

In the building of the model, we will restrict ourselves to a dynamic linear system, in which the input is a random process with known statistical properties. The system provides the output, which is, due to the condition of linearity, also a random process. These processes could be continuous or discrete. The model and its solution for continuous processes is obtained in [1] and for discrete processes in [5].

3.1 Continuous processes

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,

$v(t)$ - delivery to storehouse at time *t,*

$Q(t)$ - criterion function, complete costs.

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

Now the system will be modelled with the known equations [1]:

$$\frac{dZ(t)}{dt}=v(t)-d(t) \tag{3.1}$$

$$v(t)=u(t-\lambda) \tag{3.2}$$

$$u(t)=-\int_0^t G(\tau)Z(t-\tau)d\tau \tag{3.3}$$

In the last equation, the function $G(t)$ is the weight of the regulation that must be determined at optimum control, so that the criterion of the minimum total cost is satisfied. The lead time λ is the time period needed to activate the additional capacities in the power supply process. 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. From this point of view, let us express the total cost, the minimum of which we are trying to define, with the mathematical expectation of the square of the random variables $Z(t)$ and $u(t)$:

$$Q(t)=K_Z E\left(Z^2(t)\right)+K_u E\left(u^2(t)\right) \tag{3.4}$$

Equations represent a linear model of control in which the minimum of the mean square error has to be determined.

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 [9]:

K_Z - constant coefficient, dependent on activated resources, derived empirically,

K_u - constant coefficient, dependent on performed services and derived empirically.

3.2 Discrete processes

Similar to the continuous system, we have in similar notations in the discrete system.

Let us denote:

$Z(k)$ - activated facilities (resources, stocks) at given moment (output),

$u(k)$ - the amount of services performed (production) at a given moment,

$d(k)$ - the demand for services at a given moment (input),

κ - time elapsed between the moment the data are received and the carrying out of a service,

$Q(k)$ - criterion function, complete costs,

K_Z - constant coefficient, dependent on activated resources, derived empirically,

K_u - constant coefficient, dependent on performed services and derived empirically,

$G(k)$ - operator (weight) of regulation.

$k \in \{0, 1, 2, \ldots\}$

The dynamic linear system will then be modelled with the following difference equations:

$$Z(k) - Z(k-1) = \psi\left[v(k) - d(k)\right],\ \psi \in \mathbf{R}^{+} \tag{3.5}$$

$$v(k) = u(k-\kappa),\ \kappa \in N \tag{3.6}$$

$$u(k) = -\sum_{\kappa=0}^{\infty} G(\kappa) Z(k-\kappa) \tag{3.7}$$

$$Q(k) = K_Z E\left\{\left(Z^2(k)\right)\right\} + K_u E\left\{\left(u^2(k-1)\right)\right\}\ \textit{minimum} \tag{3.8}$$

4 FUZZY SYSTEM

Construction of a fuzzy system takes several steps [6], [7]: selection of decision variables and their fuzzification, establishing the goal and the construction of the algorithm (base of rules of fuzzy reasoning), inference and defuzzification of the results of fuzzy inference. A graphic presentation of a fuzzy system is given in Figure 2, [5].

The entire system demonstrates the course of inference from input variables against output; it is built on the basis of ‘if-then’ fuzzy rules. The fuzzy inference consists of three phases:

1. Fuzzification,
2. Fuzzy inference,
3. Defuzzification.

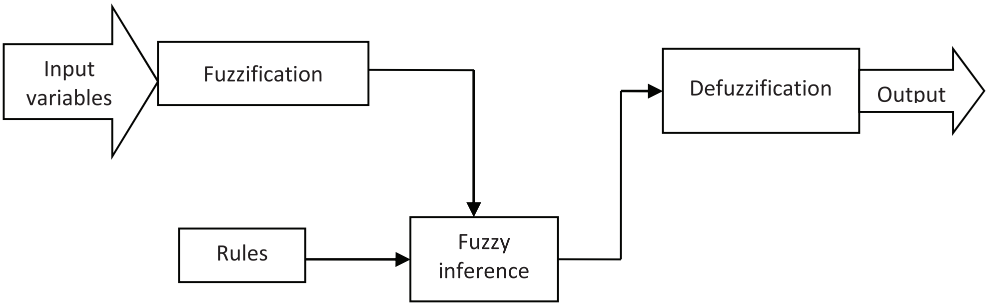

Figure 2: *The fuzzy system*

In our closed-loop model we designed a two-phase fuzzy system, given in Figure 3.

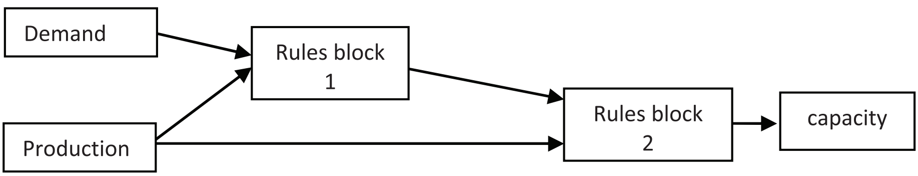

Figure 3: *The two-phased fuzzy system*

Let us assume that the demand *d* depends on [1]:

- the market area,
- the density of the area,
- the price,
- the season, and
- the uncertainty.

The demand is, in fact, the basic variable, on which the behaviour of all retailers depends. We assume that all expressions are fuzzy variables, market area, density of the area, price, season and uncertainty are input fuzzy variables, and demand is an output fuzzy variable in the first phase and in the same time also an input fuzzy variable for the second phase, Figure 4.

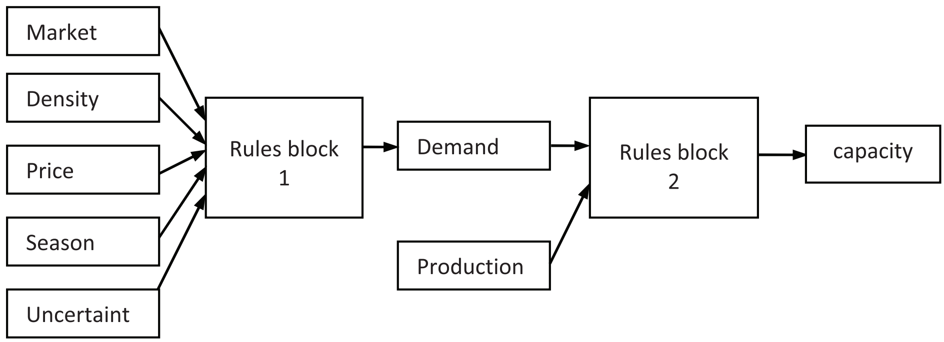

***Figure 4**: The two-phased fuzzy system with fuzzy demand in the first phase*

4.1 Fuzzification

In the fuzzification phase, fuzzy sets for all fuzzy variables (input and output) must be defined, as well as their membership functions. Every fuzzy variable is presented by more terms/fuzzy sets. In this system, there are eight fuzzy variables: the market area, the density of the area, the price, the season, the uncertainty and the demand in the first phase and the demand, and the production and the capacity in the second phase.

The fuzzy variable demand is the output of the first rules block while simultaneously being the input for the second phase (i.e. rules block 2).

Fuzzy sets are given by terms below.

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

- In the second rule block:
    g) the input fuzzy variable DEMAND is represented by: VERY_LOW, LOW, MEDIUM, HIGH, EXTREMELY_HIGH.
    h) the input fuzzy variable PRODUCTION is represented by: LOW, MEDIUM, HIGH,
    i) the output fuzzy variable CAPACITY is represented by: VERY_LOW, LOW, MEDIUM, HIGH, EXTREMELY_HIGH.

This fuzzy system is a two-phased system. The final output is CAPACITY (i.e. STOCKS) which depends on inputs DEMAND and PRODUCTION. This means that the control system is, in fact, the closed-loop system.

For every fuzzy set and for every fuzzy variable, we have to create membership functions, see Figures 5 to 12.

On the x-axis, the measures are given in units such as the number of customers, EUR, EUR/kWh, MWh and so on, depending on the data. On the y-axis, membership is measured for every possible fuzzy variable and for every fuzzy set.

Due to the simplicity in this model, we suppose that all units for all fuzzy variables are given in relative measure, i.e. percentages from 0 to 100. Of course, the expert knows what, for example, 30% for 'market area' or 80 % of the 'price' etc. means.

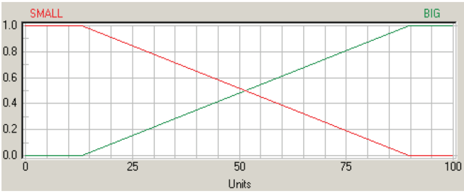

***Figure 5**: MBF of ‘MARKET’*

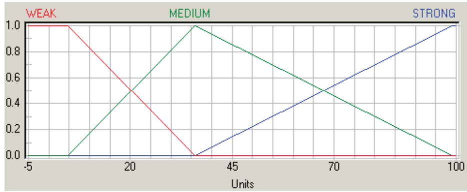

***Figure 6**: MBF of ‘DENSITY’*

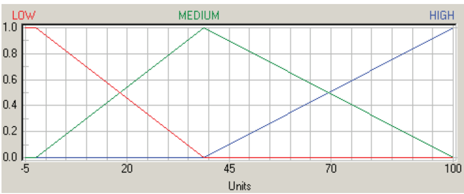

***Figure 7**: MBF of ‘PRICE’*

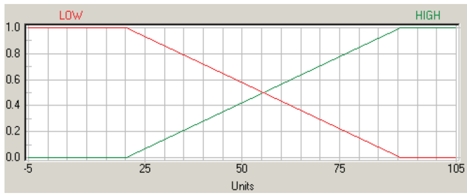

***Figure 8:** MBF of ‘SEASON’*

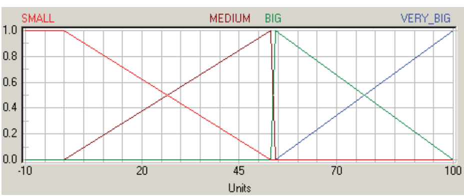

***Figure 9**: MBF of ‘ UNCERTAINTY ‘*

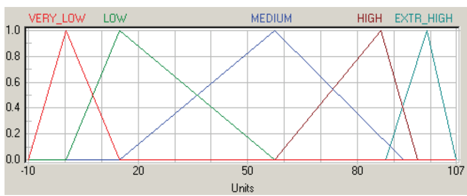

***Figure 10**: MBF of ‘DEMAND’*

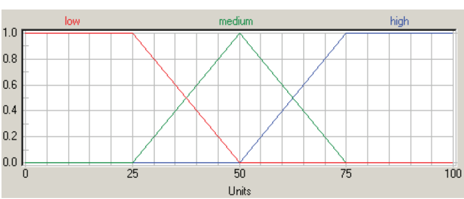

Figure 11: MBF of *‘ PRODUCTION ‘*

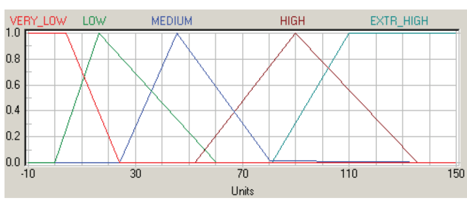

***Figure 12**: MBF of ‘* CAPACITY *‘*

4.2 Fuzzy inference

Fuzzy inference is a process in which a certain conclusion is derived from a set of fuzzy statements. In addition to linguistic variables, there are basic widgets of a fuzzy logic system as well as sets of rules that define the behaviour of a system. A single fuzzy rule (implication) assumes the form: *if x is A, then y is B,* where *A* and *B* are linguistic values defined by fuzzy sets on 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. Variables *x* and *y* are defined by the sets *X* and *Y*.

With the assembly of a base of rules, the question always appears of how to obtain the rules. Usually, this is written down as a base of knowledge within the framework of 'if-then' rules by an expert for a definite system based on his own knowledge and experiences. An expert must also define entry and exit fuzzy functions, as well as their shape and position. However, it often occurs that the expert's knowledge is not sufficient, and he cannot define an adequate number of rules. Therefore, the procedures of forming or supplementation to the base of rules based on available numerical data were developed.

With fuzzy inference, we must put all values and facts in a definite order and connect them to the procedure of inference execution, so that will be feasible do so with a computer. This order is given as a list or system of rules.

In our work, we applied FuzzyTech software (FuzzyTech, 2001), [8]. In accordance with this software tool, 144 rules in the first phase (Rule block 1) and 15 rules in the second phase (Rule block 2) were automatically created. Some of them are represented in Tables 1 and 2.

***Table 1**: Some rules Rules of the Rule Block 'RB1'*

IF					THEN	
DENSITY	**MARKET**	**PRICE**	**SEASON**	**UNCER-TAINTY**	**DoS**	**DEMAND**
WEAK	SMALL	LOW	LOW	SMALL	0.97	LOW
WEAK	SMALL	MEDIUM	HIGH	SMALL	1.00	LOW
WEAK	SMALL	HIGH	LOW	MEDIUM	0.64	VERY_LOW
WEAK	SMALL	HIGH	HIGH	VERY_BIG	1.00	LOW
WEAK	BIG	MEDIUM	LOW	BIG	1.00	LOW
WEAK	BIG	HIGH	HIGH	BIG	1.00	MEDIUM
MEDIUM	SMALL	LOW	LOW	SMALL	1.00	LOW
MEDIUM	SMALL	MEDIUM	HIGH	BIG	1.00	MEDIUM
MEDIUM	SMALL	HIGH	LOW	MEDIUM	0.75	LOW
MEDIUM	BIG	LOW	LOW	VERY_BIG	1.00	HIGH
MEDIUM	BIG	HIGH	HIGH	MEDIUM	0.63	MEDIUM
MEDIUM	BIG	HIGH	HIGH	VERY_BIG	0.20	HIGH
STRONG	SMALL	LOW	LOW	SMALL	1.00	MEDIUM

IF					THEN	
STRONG	SMALL	LOW	HIGH	MEDIUM	1.00	HIGH
STRONG	SMALL	HIGH	LOW	MEDIUM	1.00	LOW
STRONG	SMALL	HIGH	LOW	VERY_BIG	1.00	MEDIUM
STRONG	BIG	MEDIUM	HIGH	MEDIUM	0.98	HIGH
STRONG	BIG	MEDIUM	HIGH	VERY_BIG	0.73	EXTR_HIGH

Table 2: *Rules of the Rule Block 'RB2'*

IF		THEN	
DEMAND	**PRODUCTION**	**DoS**	**CAPACITY**
VERY_LOW	LOW	1.00	VERY_LOW
VERY_LOW	MEDIUM	1.00	LOW
VERY_LOW	HIGH	1.00	LOW
LOW	LOW	1.00	LOW
LOW	MEDIUM	1.00	LOW
LOW	HIGH	1.00	MEDIUM
MEDIUM	LOW	1.00	LOW
MEDIUM	MEDIUM	1.00	MEDIUM
MEDIUM	HIGH	1.00	HIGH
HIGH	LOW	1.00	MEDIUM
HIGH	MEDIUM	1.00	HIGH
HIGH	HIGH	1.00	HIGH
EXTR_HIGH	LOW	1.00	HIGH
EXTR_HIGH	MEDIUM	1.00	HIGH
EXTR_HIGH	HIGH	1.00	EXTR_HIGH

4.3 Defuzzification

Results from the evaluation of fuzzy rules is fuzzy. Defuzzification is the conversion of a given fuzzy quantity to a precise, crisp quantity. In the procedure of defuzzification, fuzzy output variables are changed into crisp numerical values. There are many procedures for defuzzification, which give different results.

The most frequently method used in praxis is CoM-defuzzification (the Centre 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, [6]. CoM is a type 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*.

As already mentioned, there are many methods of defuzzification that generally give various results. In our example, our model is created by FuzzyTech 5.55i software, and we use the Centre of Maximum (CoM) defuzzification method.

4.4 Optimisation

When the system structure is set and all elements of the system are defined, the model must also be tested and checked for its fit to data and for whether it produces the desired results. In our case, we have tasks with relatively simple optimization, because we have limited the problem to concrete conditions. We simplified the system so that it is well defined and gives the desired results. During optimization, we verify the entire definition area of input data. For each point of the definition area, we check whether the system is giving the desired result and if this result is logical. If we are not satisfied with the results, we can change any of the membership functions or any of the fuzzy inference rules.

For optimisation, there are various methods, such as trial and error, or using graphic tools that can visually demonstrate system activity. Such a graphic demonstration shows us the response to a change of data or change in the definition of the system elements, [8]. One of the most efficient methods is using neural nets during the neuro-fuzzy training to obtain good and regular results.

4.5 Neuro-fuzzy training

To optimise our results and to obtain a stable and robust fuzzy model, we have to perform neuro-fuzzy training, [9], [10]. At this point, help from an expert who knows the system very well is required. Suppose that we have a base of knowledge and we can start our neuro-fuzzy procedure. We have used FuzzyTech software's option for neuro-fuzzy learning in the first phase, [1]. Making 500 iterations in the phase of training (35 samples) and 500 iterations in the phase of checking (also 35 samples), we have changed the shapes of the membership functions for all fuzzy variables and also changed the weights (DoS) for some rules for fuzzy inference in Rules block 1. When comparing expert and fuzzy results, the statistical data are the following: the average deviation (expert results vs. fuzzy results) is 1.74%, 16 data points (samples) between 0 and 1%, 9 data points between 1 and 2%, 5 between 2 and 4% and 5 data points between 4 and 8%.

5 NUMERICAL EXAMPLE

When we have a robust fuzzy system, we can start numerical simulations. Using FuzzyTech software, we can simulate all possible situations interactively. Some results in Phase 1 are given in Table 3. The first five columns represent input fuzzy variables; the last column 'demand' as output of the fuzzy system is divided into two sub-columns. In the first, we can see crisp values of demand before neuro-fuzzy training and, in the second, values after neuro-fuzzy training.

Table 3: *Some numerical results in phase 1*

Density	Market	Price	Season	Uncertainty	Demand	
					before training	after training
0	0	100	0	0	0	1
50	50	50	50	50	60	50
100	100	1	100	100	100	100
30	30	80	80	50	50	42
70	50	90	20	90	45	58
60	100	40	50	50	77	73
60	60	30	50	50	71	67
70	70	90	90	70	72	76
90	50	100	100	100	74	78
50	30	80	20	20	31	28
19	33	49	66	66	53	52
39	70	60	60	50	52	54
78	78	39	78	78	88	80

Of course, in the table, we merely have some results, but with the interactive simulation that is possible with FuzzyTech software, we can simulate every situation. The quality of the results depends on the expert who prepares a data file for the neuro-training procedure.

After optimization of the first subsystem (Phase 1), we can also run the fuzzy system in Phase 2. Some numerical results are presented in Table 4, in which the fuzzy variables of density, market, price, season, uncertainty and production are inputs, and the fuzzy variable capacity is the output of a two-phased fuzzy system. The fuzzy variable demand is an output in the first subsystem while simultaneously being an input to the second subsystem, i.e. the second phase in the entire fuzzy system.

Table 4: *Some numerical results in two-phased fuzzy system*

Density	Market	Price	Season	Uncertainty	Production	Capacity
90	98	10	100	95	90	116
50	50	50	50	50	50	50
100	100	1	100	100	100	90
30	30	80	80	50	50	34
70	50	90	20	90	90	68
60	100	40	50	50	80	90
60	60	30	50	50	80	60
70	70	90	90	70	70	72
90	50	100	100	100	70	82
50	30	80	20	20	30	23
20	40	40	60	50	80	65
40	70	60	60	50	100	70
78	78	39	78	78	10	41

6 CONCLUSION

A theoretical mathematical model of system control can also be used in an energy technology system and in all its subsystems. Input-output signals are discrete or continuous functions. For operations, many conditions have to be fulfilled. During the control process, a great deal of information must be processed, which can only be done if a transparent and properly developed information system is available. The solution, i.e. optimal control, depends on many numerical parameters. All data and numerical analysis can only be processed into information for control if high quality and sophisticated software and powerful hardware are available.

For the study of the structure, interrelationships and operation of a phenomenon with system characteristics, the best method is the general systems theory. When we refer to system technology as a synthesis of organization, information technology and operations, we have to consider its dynamic dimension when creating a mathematical model. As each such complex phenomenon makes up a system, the technology in this article is again dealt with as a dynamic system. Elements of the technological system compose an ordered entity of interrelationships and thus allow the system to perform production functions. During the control process, a great deal of information must be processed, which can only be done if a transparent and properly developed information system is available. Models of optimum control can also be used in the power station system.

The fuzzy approach in creating the mathematical model with which we are describing the system can be successful in the case that we have a good robust base of expert knowledge. With appropriate computer tools, an algorithm can be used for concrete numerical examples.

References

[1] **J. Usenik**: *Mathematical model of the power supply system control.* Journal of Energy Technology, Aug. 2009, vol. 2, iss. 3, str. 29-46

[2] **J.J. DiStefano, A.R. Stubberud, I.J.Williams**: *Theory and Problems of Feedback and Control Systems,* McGraw-Hill Book Company, 1987

[3] **J. Usenik**: *Control of Traffic System in Conditions of Random or Fuzzy Input Processes,* Promet-Traffic-Traffico, 2001, Vol. 13 no. 1, pp. 1–8

[4] **J. Usenik:** *Fuzzy dynamic linear programming in energy supply planning,* Journal of energy technology, 2011, vol. 4, iss. 4, pp. 45-62

[5] **J. Usenik, M. Repnik**: *System control in conditions of discrete stochastic input processes,* Journal of energy technology, Feb. 2012, Vol. 5, iss. 1, pp. 37-53

[6] **J. T. Ross**: *Fuzzy Logic with Engineering Applications*, second edition, John Wiley&Sons Ltd,The Atrium, Southern Gate, Chichester, 2004

[7] **H. J. Zimmermann**: *Fuzzy Set Theory - and Its Applications*, 4th edition, Kluwer Academic Publishers, Dordrecht, 2001

[8] *FuzzyTech, Users Manual*, 2001, INFORM GmbH, Inform Software Corporation

[9] **J. Usenik, M. Bogataj**: *A fuzzy set approach for a location-inventory model.*Transp. plann. technol., 2005, vol. 28, no. 6, pp. 447–464

[10] **J. Usenik, T. Turnšek:** *Modelling conflict dynamics in an energy supply system.* Journal of energy technology, Aug. 2013, Vol. 6, iss. 3, pp. 35-45

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NUMERICAL ANALYSIS OF A HEAT EXCHANGER: ANSYS VS SOLIDWORKS

NUMERIČNA ANALIZA TOPLOTNEGA PRENOSNIKA: ANSYS IN SOLIDWORKS

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Keywords: numerical analysis, heat exchanger, Ansys CFX, SolidWorks

Abstract

In this article, three-dimensional numerical analyses are presented with the goal of investigating heat transfer and fluid flow characteristics of an un-baffled shell-and-tube heat exchanger, using Ansys CFX and SolidWorks Flow Simulation software packages. The analyses of the overall heat transfer coefficient and pressure drop values inside the shell and tubes were performed on designed meshes with similar number of elements, for various Reynolds numbers. All numerically obtained results were validated with experimental measurements from literature.

Povzetek

V članku so predstavljeni rezultati in izvedba tridimenzionalnih numeričnih analiz prenosa toplote za primer cevno paketnega prenosnika toplote. Za izvedbo numeričnih simulacij sta bila uporabljena programska paketa Ansys CFX ter SolidWorks Flow Simulation. Analiza skupnega koeficienta prenosa toplote ter tlačnih padcev v ceveh in plašču je bila izvedena s strukturirano mrežo za več Reynoldsovih števil. Z namenom, da ovrednotimo rezultate numeričnih simulacij, smo le te primerjali z eksperimentalno pridobljenimi vrednostmi iz literature.

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1 INTRODUCTION

Heat exchangers are one of the most commonly used pieces of equipment in numerous mechanical industries and home appliances. They are used to transfer heat between two process streams in various processes that involve cooling, heating, condensation, boiling and evaporation. Different heat exchangers are named according to their applications. For instance, heat exchangers being used to boil are known as boilers, while heat exchangers for condensation purposes are called condensers.

Heat exchangers are available in many configurations and are classified according to their application, process fluids, or mode of heat transfer and flow. They can also be classified based on shell and tube passes, types of baffles, arrangement of tubes, and whether they have smooth or baffled surfaces. Heat exchangers can transfer heat through convection or conduction. There are two primary flow arrangements in the heat exchanger: a parallel-flow and a counter-flow. Two fluids flow from the same end to another end in a parallel flow heat exchanger. For the counter-flow arrangement, the two fluids run in the opposite direction from two ends of the heat exchanger. The selection of a particular heat exchanger configuration depends on several factors, which may include the area requirements, maintenance, flow rates and fluid phase, [1].

Shell-and-tube heat exchangers (STHE) consist of a bundle of tubes enclosed within a cylindrical shell. Two fluids, of different starting temperatures, flow through the heat exchanger. One fluid flows through the tubes and the other flows outside the tubes but inside the shell. Heat is transferred from one fluid to the other through the tube walls, either from tube side to shell side or vice versa. The fluids can be either liquids or gases on either the shell or the tube side. Most commonly used STHE have large heat transfer surface area-to-volume ratios to provide increased heat transfer efficiency. Shell and tube heat exchangers are simple to manufacture for a large variety of sizes and flow configurations and can operate at high pressures and high temperatures. The STHE can be employed for processes that require large quantities of fluid to be heated or cooled. They are easy to clean and repair in case of malfunction and offer greater flexibility of mechanical features to withstand any service requirement, [2].

The performance and efficiency of heat exchangers are measured through the amount of heat being transferred using the area of heat transfer and the pressure drop. Its efficiency is usually defined with an overall heat transfer (HT) coefficient, [1]. Thus, in order to calculate these parameters, the flow distribution and temperature fields inside the shell and tubes must be obtained. For this reason, several CFD (computational fluid dynamics) flow simulations of simple un-baffled STHE are carried out, using the Ansys CFX and SolidWorks Flow Simulation (SWFS) software packages and compared to experimental data from literature, [1].

2 GOALS

With the aim of investigating the difference between used numerical software packages, three-dimensional CFD simulations were carried out to obtain counter-current STHE global parameters. The difference of the software packages' purposes and limitations must be emphasized. Ansys CFX is a well-known commercial standalone CFD software for numerical analyses, while SolidWorks Flow Simulation is a part of CAD (computer-aided design) package.

The geometry of the heat exchanger was modelled in SolidWorks (SW). We created corresponding meshes in SWFS and in ICEM CFD software. Simulations were carried out in order to resolve the heat transfer coefficient and pressure drop characteristics of the heat exchanger for different Reynolds numbers ranging from $9.2 \cdot 10^4$ to $15.2 \cdot 10^4$ for the shell and from $2.16 \cdot 10^4$ to $3.6 \cdot 10^4$ for tubes. The designed meshes with associated boundary conditions were iteratively solved with steady-state solvers using different turbulence models. In order to validate the numerically obtained results, we compared them to existing experimental measurements from literature, [1].

3 NUMERICAL APPROACH

The heat exchanger numerical model was simulated assuming steady-state conditions, using conventional Reynolds averaged Navier-Stokes (RANS) turbulence models. In general, for modelling the turbulent flow and heat transfer processes, two equation models are most commonly used, [1]. SWFS provides only the k-ε turbulence model, while Ansys CFX offers various choices. In order to obtain the most suitable turbulence model, multiple test calculations were carried out and obtained results were compared with experimental measurements from literature. The model that most accurately predicts the results was used for further calculations.

3.1 Geometry

The three-dimensional STHE geometry was designed in the SW software package in accordance with the prescribed dimensions from [1]. The geometry consisted of four main parts: shell, inlet tube, outlet tube and nineteen inner tubes. Table 1 presents description and dimensions of the STHE geometry in millimetres.

Table 1: *Dimensions of the heat exchanger geometry.*

Description	Value [mm]
Overall dimensions	54 × 378 × 5850
Shell diameter	108
Tube outer diameter	16
Tube inner diameter	14.6
Shell/tube length	5850
Inlet tube length	70
Outlet tube length	200

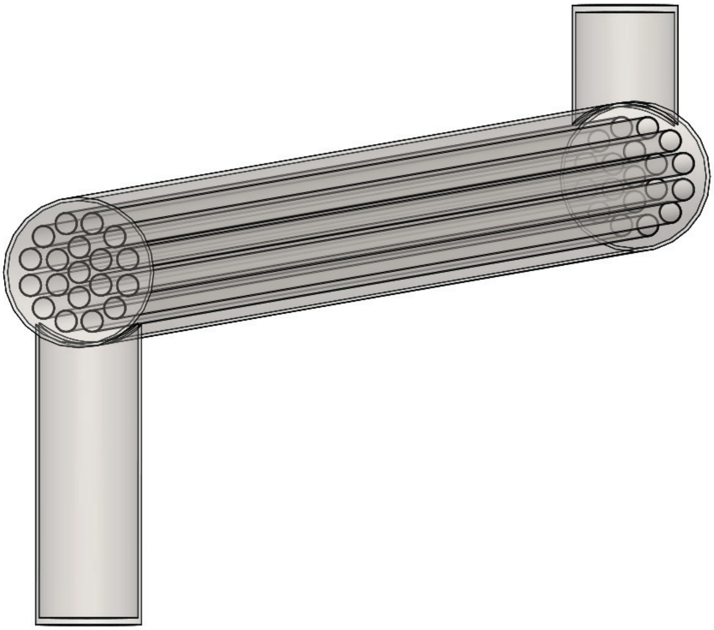


Figure 1: *Heat exchanger model.*

3.2 Numerical mesh

In CFD, the numerical mesh has two elementary functions: first, definition of the modelled geometry; second, discretization of the computational domain. The constructed mesh has to describe the physical geometry of the modelled object. The complexity of the modelled object affects the final mesh size and consequently the required design time. The amount of computer resources needed for the calculation of numerical simulations is proportional to the mesh intersection density and longitudinal resolution. The accuracy for solving the governing equations is dependent on the number of discrete elements and nodes of the mesh. Generally, a numerical solution becomes more accurate when a mesh with a greater resolution is used. Furthermore, a mesh with smaller element size is usually used in regions where high temperature and pressure gradients of critical quantities are occurring. In numerical simulations, we have to balance accuracy with the limitations of computer resources.

Structural computational meshes for fluid and solid domains of the shell, inlet tube, outlet tube, and inner tubes were designed with a pre-processor ICEM CFD for the analysis in Ansys CFX software. Once the partial volume meshes are created, they were merged in Ansys CFX to represents the full computational domain. In SW, the mesh was designed with an in-built mesh manager in SWFS software package for the modelled domain.

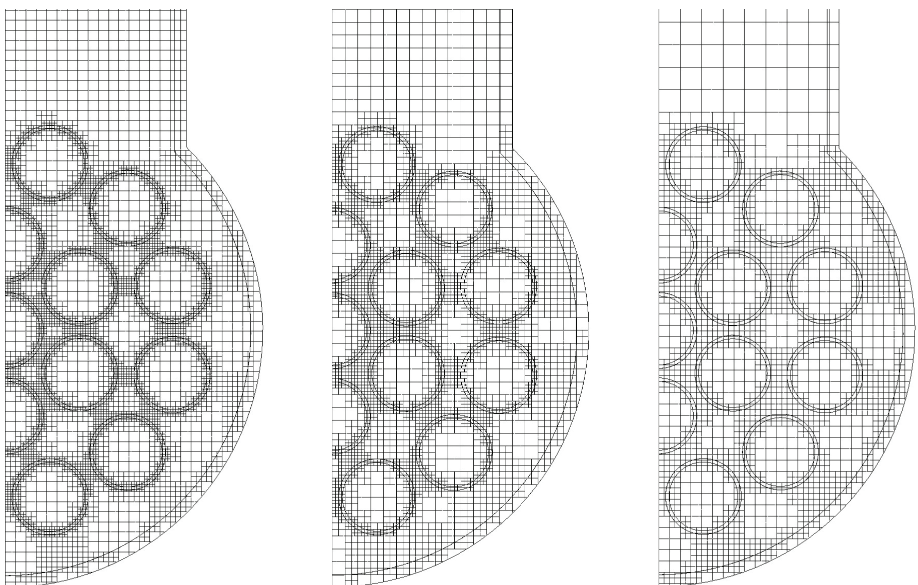
3.2.1 SolidWorks Flow Simulation

In order to acquire grid-independent results, several test calculations of the pressure drop in the shell and tubes, as well as the HT coefficient, were performed in SWFS. Three meshes with different number of elements were designed and used for performing simulations at inlet velocities of 1.2 m/s for the shell and 1.8 m/s for tubes with the corresponding boundary conditions described in Chapter 3.3. The deviation between numerically obtained results and experimental values from [1] is presented in Table 2.

Table 2: *Deviation between numerically obtained results and experimental values for different mesh resolutions.*

Mesh resolution (approx. number of elements)	Coarse (2,000,000)	Medium (3,500,000)	Fine (5,000,000)
Pressure drop deviation in shell [%]	-22.34	-17.90	-16.32
Pressure drop deviation in tubes [%]	5.66	4.27	5.51
Overall HT coefficient deviation [%]	-14.23	-9.20	-8.85

From Table 2, it is evident that the calculation results do not deviate remarkably between the medium and fine mesh. From that, it can be concluded that the mesh density does not significantly affect the calculation results in this case and the medium-sized mesh was used as a reference for further simulations in SWFS as optimal mesh density.



a) b) c)

Figure 2: *Mesh resolutions a) course, b) medium and c) fine.*

3.2.2 ICEM CFD

As the reference mesh for computation in SW had approximately 3.5 million elements, we decided to design a mesh with comparable number of elements in ICEM CFD for the analysis in Ansys CFX.

A dimensionless wall distance (y^+) value plays an important role in turbulence modelling for the near wall treatment. In order to resolve the boundary layer sufficiently, inflation on the walls was created and y^+ simulations were calculated. Precise computed results were possible only if the resolution of the mesh near the walls satisfied the condition $y^+ < 1$.

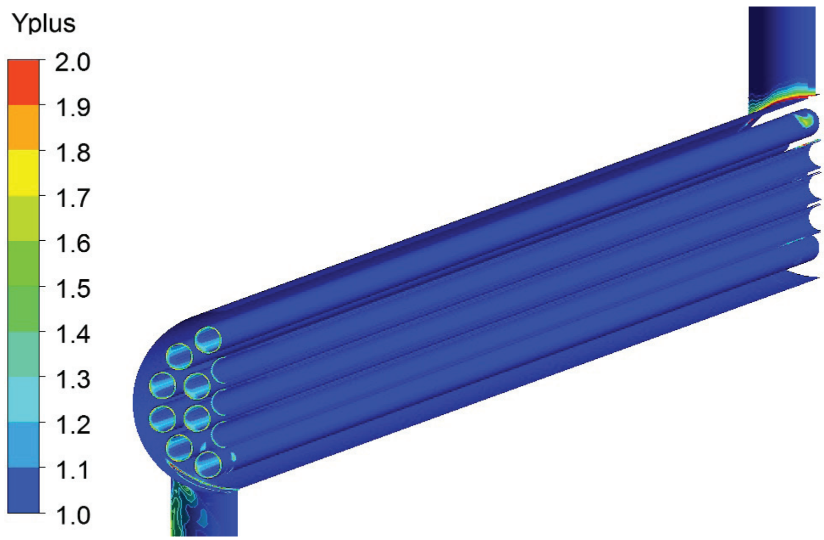


Figure 3: *y^+ value for the shell Reynolds number $13.68 \cdot 10^4$.*

Different turbulence models available in Ansys CFX were evaluated to investigate their application for our case. As seen in Table 3, the overall HT coefficient and pressure drop obtained from these models were compared (in %) to the experimental results [1].

Table 3: *Turbulence model comparison of overall HT coefficient and pressure drop.*

Turbulence model	**SST**	***k-ω***	***k-ε***	**RNG *k-ε***
Pressure drop in shell deviation [%]	-1.57	-3.30	19.32	21.24
Pressure drop in tubes deviation [%]	-14.54	-20.87	-8.98	-0.06
Overall HT coefficient deviation [%]	-0.20	-1.85	14.54	15.14

Based on the results in Table 3, the SST model was chosen for further analysis.

In Figure 4, the designed meshes are shown, which clearly represent different types of mesh creation. A Cartesian-based mesh generated in SWFS, [3], and a typical structured mesh designed in ICEM CFD are presented.

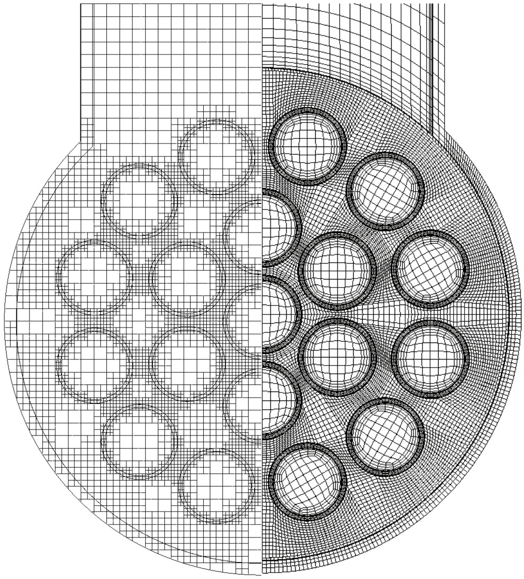


Figure 4: *Designed meshes in SWFS (left) and in ICEM CFD (right) used for analysis.*

As seen in Figure 4, the number of elements seems greater in ICEM CFD than in SWFS. SWFS only provides Cartesian-based mesh generation [3], which, when refinement is used, splits an element in half along all three coordinate axis (an element cannot be split in only one axis). Thus, where the mesh refinement is used, there are up to four times more elements along the length of the model in SWFS than in ICEM CFD. Therefore, it is difficult to achieve the same number of elements in the longitudinal direction.

3.3 Boundary conditions and convergence criteria

For achieving good correlation with experimental results, precise boundary conditions needed to be applied to the model.

The shell inlet was defined as a velocity inlet with an initial temperature of 317 K. The tube inlet was also defined as a velocity inlet with an initial temperature of 298 K. Outlets for both shell and tube were defined as pressure outlets with atmospheric pressure. The outer walls were set as adiabatic. The tube walls were set for transferring of heat between the shell and tube side fluids. The symmetry boundary condition was applied for both software packages.

To satisfy the convergence criteria, the residual type was set to root mean square (RMS) with the target value of $1 \cdot 10^{-5}$. We also set the number of maximum iterations to 500 and automatic timescale control. Both software packages have an automatic system for stopping the analysis when it reaches the defined convergence criteria. In Ansys, we encountered a problem with convergence, so we inserted monitor points to monitor the desired parameters. The simulation was stopped when the selected parameters ceased altering their values.

4 RESULTS

4.1 Pressure drop

Pressure drop values at different Reynolds numbers were acquired from both software packages and calculated directly from CFD results. These results were compared with available experimental data from [1] and are presented in Table 4 and Table 5, respectively.

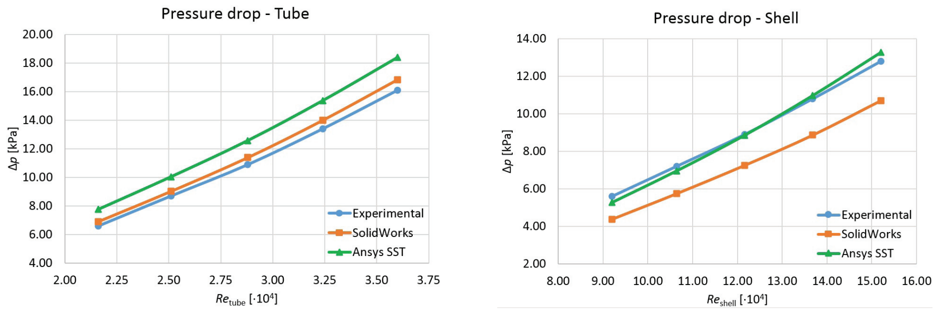
Table 4: *CFD and experimental results of pressure drop [1].*

Reynolds number [·10^4]		Ansys SST model Pressure drop [kPa]		SolidWorks Pressure drop [kPa]		Experimental Pressure drop [kPa]	
Shell	Tube	Shell	Tube	Shell	Tube	Shell	Tube
9.20	2.16	5.28	7.74	4.37	6.89	5.60	6.60
10.64	2.52	6.96	10.02	5.74	9.01	7.20	8.70
12.16	2.88	8.85	12.56	7.25	11.37	8.90	10.90
13.68	3.24	10.97	15.35	8.87	13.97	10.80	13.40
15.20	3.60	13.26	18.37	10.71	16.81	12.80	16.10

Table 5: *Deviation between CFD and experimental results of pressure drop.*

Reynolds number [·10^4]		Ansys SST model Pressure drop deviation [%]		SolidWorks Pressure drop deviation [%]	
Shell	Tube	Shell	Tube	Shell	Tube
9.20	2.16	-5.70	17.32	-21.98	4.38
10.64	2.52	-3.37	15.22	-20.32	3.53
12.16	2.88	-0.51	15.23	-18.54	4.31
13.68	3.24	1.57	14.54	-17.90	4.27
15.20	3.60	3.62	14.11	-16.33	4.42

The pressure drop in shell is under-predicted by SW with a deviation of 16–22%, whereas the pressure drop in tubes is over-predicted by approximately 4%. In Ansys CFX, the pressure drop in the shell is under-predicted with a deviation of 1–6%. The deviation in tubes is over-predicted by 14–17%. Generally, Ansys better predicts the pressure drop in the shell by 16%, while SW computed better results for the tube pressure drop by about 11%, as presented in Table 5 and presented as graphs in Figure 5.



a) b)

Figure 5: *Comparison of pressure drop on a) shell side and b) tube side.*

4.2 Overall heat transfer coefficient

From numerical simulations, we acquired heat transfer rate values and temperatures from which we calculated the overall heat transfer coefficient U with equation:

$$U = \frac{\dot{Q}}{A \cdot \Delta T_{\mathrm{LM}}}, \tag{4.1}$$

where:

$\dot{Q}$ - heat transfer rate;

A - heat transfer surface area;

ΔT_{LM} - logarithmic mean temperature difference.

The logarithmic mean temperature difference ΔT_{LM} or LMTD is calculated to estimate the average temperature difference throughout the heat exchanger. It's defined with equation:

$$\Delta T_{\mathrm{LM}} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}, \tag{4.2}$$

where:

ΔT_1, ΔT_2 - the temperature difference between the two streams.

For counter-current flow in the shell and tube heat exchangers, the temperature difference is defined with $\Delta T_1 = T_{\mathrm{Hot\_In}} - T_{\mathrm{Cold\_Out}}$ and $\Delta T_2 = T_{\mathrm{Hot\_Out}} - T_{\mathrm{Cold\_In}}$. The inlet temperature for the shell was set to $T_{\mathrm{Hot\_In}}$=317 K and for tubes to $T_{\mathrm{Cold\_In}}$=298 K. The temperatures $T_{\mathrm{Cold\_Out}}$ and $T_{\mathrm{Hot\_Out}}$ were numerically obtained.

Table 6: *CFD and experimental results of an overall HT coefficient [1].*

Reynolds number [·10⁴]		Ansys SST model	SolidWorks	Experimental
Shell	Tube	Overall HT coefficient [W/m²·K]	Overall HT coefficient [W/m²·K]	Overall HT coefficient [W/m²·K]
9.20	2.16	1847	1785	1965
10.64	2.52	2114	1997	2196
12.16	2.88	2367	2195	2414
13.68	3.24	2626	2375	2621
15.20	3.60	2879	2548	2819

Table 7: *Deviation between CFD and experimental results of an overall HT coefficient.*

Reynolds number [·10⁴]		Ansys SST model	SolidWorks
Shell	Tube	Overall HT coefficient deviation [%]	Overall HT coefficient deviation [%]
9.20	2.16	-5.99	-9.18
10.64	2.52	-3.75	-9.05
12.16	2.88	-1.96	-9.07
13.68	3.24	0.20	-9.38
15.20	3.60	2.14	-9.63

The overall HT coefficient is under-predicted by SW by approximately 9%. In Ansys CFX, the overall HT coefficient is under-predicted with a deviation of 1–6%. Generally, the Ansys SST turbulence model better predicts the overall HT coefficient by 4–8%, as seen in Table 7 and Figure 6.

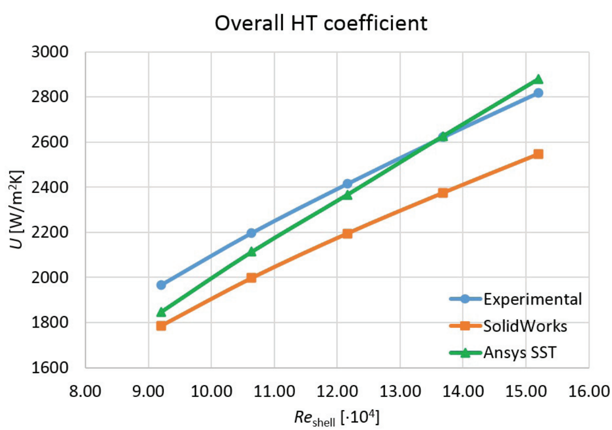


Figure 6: *Comparison of overall heat transfer coefficient.*

5 CONCLUSIONS

Simulations of the shell-and-tube heat exchanger global parameters for various Reynolds numbers were made in order to compare the results from different software packages and then validate them with experimental data as a reference.

For this CFD study, numerical meshes for the geometry seen in Figure 1 were designed. Grid independence was studied with three meshes designed in SWFS, comprised of different numbers of elements (Table 2) with corresponding boundary conditions. Based on the results, the medium-sized mesh has been recognised as suitable and was chosen for further analyses. A mesh with a comparable number of elements was designed in ICEM CFD for the analysis in Ansys CFX. In the process of the mesh design, a dimensionless wall distance (y^+) value was considered.

Different turbulence models were available and evaluated to investigate their application for this case. The tested turbulence models were SST, *k-ω, k-ε* and RNG *k-ε.* As seen in Table 3, the SST model computed the most comparable results for the shell pressure drop and overall HT coefficient with experimental data, while the RNG *k-ε* model computed the best results for the pressure drop in tubes. Based on all three categories, the chosen model for further computation was the SST turbulence model.

Further simulations were done for Reynolds numbers ranging from $9.2 \cdot 10^4$ to $15.2 \cdot 10^4$ for the shell and from $2.16 \cdot 10^4$ to $3.6 \cdot 10^4$ for tubes. As presented in Table 5 and seen in Figure 5, the pressure drop in the shell is under-predicted by SW with a deviation of 16–22%, whereas the pressure drop in tubes is over-predicted by approximately 4%. In Ansys CFX, the pressure drop in the shell is under-predicted with a deviation of 1-6%. The deviation in tubes is over-predicted between 14 and 17%. Generally, Ansys CFX better predicts the pressure drop in the shell by 16%, while SW computed better results for the tube pressure drop by about 11%.

The overall HT coefficient was also simulated for all above mentioned Reynolds numbers, as seen in Table 7 and Figure 6. SWFS under-predicts the result by approximately 9%. In Ansys CFX, the SST turbulence model under-predicted the overall HT coefficient with a deviation of 1–6%. In general, Ansys CFX better predicts the overall HT coefficient by 4–8%.

Based on the computed results of the pressure drops and the overall HT coefficient, the Ansys SST turbulence model would be the better choice for the example used in this paper. Nevertheless, if we take into account the time and effort to make a structured mesh in ICEM CFD, SWFS would be sufficient for this CFD problem since the results are comparable.

References

[1] **U. U. Rehman:** *Heat Transfer Optimization of Shell-and-Tube Heat Exchanger through CFD Studies*, Master's Thesis, Chalmers University of Technology, Department of Chemical and Biological Engineering, 2011

Available at: http://publications.lib.chalmers.se/records/fulltext/155992.pdf,

Accessed on December 13, 2014

[2] **H. Kotwal, S. Patel:** *CFD Analysis of Shell and Tube Heat Exchanger - A Review*, International Journal of Engineering Science and Innovative Technology (IJESIT), Volume 2, Issue 2, 2013

Available at: http://www.ijesit.com/Volume%202/Issue%202/IJESIT201302_49.pdf,

Accessed on December 13, 2014

[3] **A. Sobachkin, G. Dumnov:** *Numerical Basis of CAD-Embedded CFD,* 2014

Available at: http://www.solidworks.com/sw/docs/Flow_Basis_of_CAD_Embedded_CFD_Whitepaper.pdf, Accessed on October 6, 2014

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BUSINESS MODELS FOR ENERGY PERFORMANCE CONTRACTING

POSLOVNI MODELI ENERGETSKEGA POGODBENIŠTVA

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Keywords: Energy performance contracting, investment, energy efficiency, sustainable development, business model, building renovation

Abstract

Energy performance contracting is a financial mechanism that can be used to jointly address the issues of increasing energy independence, as well as reducing greenhouse gas emissions and energy consumption. Moreover, energy performance contracting could substantially contribute in engaging socio-economic issues in parallel, including economic growth, job creation, social cohesion and other aspects relevant to sustainable development. This article will attempt to demonstrate the specifics of different EPC business models and how they can contribute to ambitious energy-saving targets for the year 2050.

Povzetek

Energetsko pogodbeništvo je finančni mehanizem, katerega se lahko uporabi pri skupni obravnavi relevantnih problemov kot so povečevanje energetske samozadostnosti, zniževanje emisij toplogrednih plinov ter zmanjšanje rabe energije. Še več, energetsko pogodbeništvo lahko pomembno prispeva k reševanju socialno-ekonomskih vprašanj kot so rast gospodarstva, ustvarjanje delovnih mest, družbena kohezija in ostalih faktorjev, ki so pomembni za trajnostni razvoj. V tem članku je predstavljenih nekaj posebnosti izbranih poslovnih modelov energetskega pogodbeništva, z uporabo katerih lahko pomembno prispevamo k uresničenju ambicioznih ciljev zniževanja rabe energije do leta 2050.

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1 INTRODUCTION

Since 2009, most economies of developed nations around the globe have struggled to generate and sustain job growth. Despite the tightening of the labour market in recent years, trailing the slow but stable economic recovery, unemployment remains at high levels, particularly among highly educated and young job seekers. Facing the growing tensions between generations and classes, fuelled by an unprecedented rise in income inequality, policymakers desire sustainable solutions to mitigate brain drain, impoverishment, and social exclusion by creating permanent employment opportunities. Energy efficiency investments can stimulate a net increase in employment in two major ways and, as such, can greatly contribute to comprehensively addressing various aspects of sustainable development, emphasizing the importance of social cohesion in our culture.

Primarily, the implementation of energy efficiency projects, either through upgrades in technical equipment, refurbishment of buildings' thermal envelopes, awareness raising/promotional/skill development or any type of comparable measures, foster the direct creation of jobs as the projects are carried out; secondly, the saved costs on energy are eligible to be retained and reinvested in the advancement of the same project or in the broader economy. Additionally, a pervasive implementation of energy efficiency projects further encourages and strengthens a wider variety of products and services (e.g. for energy management services, energy auditing, information and communication technology for personal energy accounting, energy-saving appliances and lighting systems, etc.), supplied by enterprises present in the region, nation, or anywhere in the EU.

Considering the need to mitigate limitations of strained public finances as well as several other challenges, it is sensible to pursue investment in energy efficiency on the basis of public-private partnerships on the EPC business model.

This model is especially attractive for the refurbishment of publicly owned infrastructure, as both the national and local budgets of developed countries are burdened by mandates for reduced public spending in addition to the lack of technical and operational expertise of their personnel to carry out and manage such projects. The building sector accounts for almost 40% of total final energy consumption in the EU, [1], which in itself offers tremendous potential for energy savings and investment. Furthermore, within the paradigm of reducing carbon emissions, each EU member state is required under Directive 2010/31/EU on the energy performance of buildings to renovate 3% of its total building stock surface every year, which is also transposed into Slovenian legislation under the renewed Energy Act EZ-1, [2]. This provides investment in energy efficiency with a solid legal framework and future outlook, which will partially be carried out by coupling public and private interest for achieving sustainable development through the EPC mechanism. It is perhaps the best way to address the interconnected issues of energy independence, climate change, social inequality, and job growth.

2 GENERAL COST AND SAVING DISTRIBUTION IN EPC PROJECTS

Energy performance contracting is an innovative financing model used to fund investment in energy efficiency and renewable energy sources (RES), which are in turn financed through reductions in overall costs. The services related to implementation measures are realized through an agreement with an external party, a so-called Energy Saving Company (ESCO) that assumes the investment, technical, operational and other associated risks and utilizes the income generated either by energy efficiency or by implementation of renewable energy production to repay the initial capital investment plus profit. The ESCO guarantees the projected level of energy savings (or energy production) and bases its profit margin on the effectiveness of implemented measures.

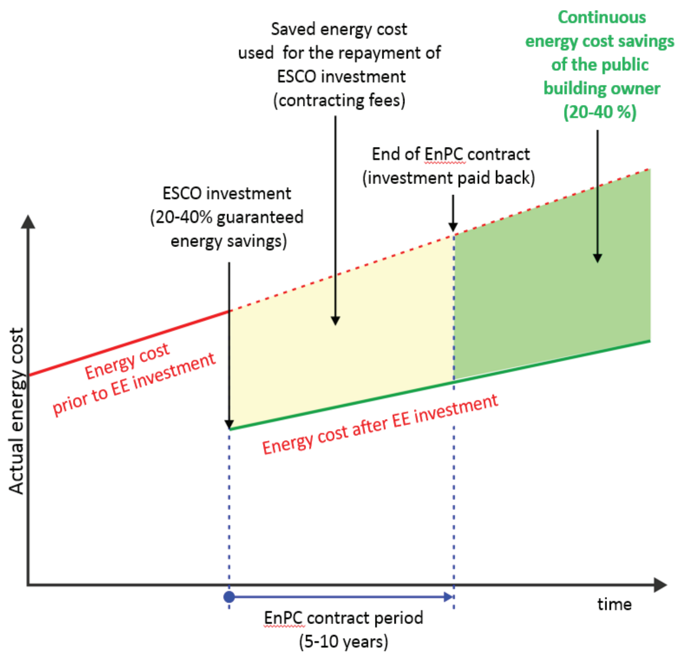

Figure 1: *A schematic presentation of energy cost projection (recapitalization and profit of the ESCO) before and after carried out refurbishment measures (Source: Chart provided by GIZ - Deutsche Gesellschaft für Internationale Zusammenarbeit)*

As described, the chart illustrates the reduced energy costs due to investment in energy efficiency measures. The chart features a linear growth trend for the cost (price) of energy, which has not yet materialized, mainly due to the slowdown in economic activity in China as well as production increases in the USA (fracking sources), as well as additional oil supplied by Russia. Even in a static energy price environment, the concept remains valid, although the payback period is slightly longer, and the future profit margin for the ESCO is somewhat reduced.

3 EPC MODELS PERTINENT TO VARIED LEVELS OF REFURBISHMENT

There are many methods for structuring a contract; therefore, it is difficult to extensively define all possible variations of EPC business models. However, the contracts broadly fall into certain groups that share many aspects.

Several types of EPC business models, which use different approaches to implementing energy efficiency (or renewable energy) projects, are available on the service market today. They differ in many aspects, the most relevant of which are investment requirements, risk distribution and duration of the contract. Among the many known models, the most frequently applied ones typically fall into one of the following categories, [3]:

- Shared savings contract: The customer shares an agreed portion of savings with the ESCO.
- Guaranteed Savings Contract: The ESCO assumes performance risks by guaranteeing energy savings.
- Variable Contract: The ESCO receives a defined amount of savings every year until the ESCO has been paid its original costs.
- Integrated EPC contract: Combination of Energy Performance and Energy Supply Contracting
- Comfort contract (Chauffage): ESCO takes over complete responsibility for the provision to the client of an agreed set of energy services
- EPC Plus contract: Deeper renovations/ comprehensive refurbishments are included; the payback time is longer than the contract; co-financing by the owner, by public funds or others
- EPC light contract: Savings are achieved through organisational measures with low or no investments in technical equipment, energy saving is guaranteed by the ESCO.

A comprehensive review of implemented energ-saving projects utilizing the EPC model within the preliminary analysis carried out in nine countries (Germany, Greece, Croatia, Slovenia, Slovakia, Serbia, Romania, Latvia, and the Ukraine) was implemented under a coordination and support project funded under Horizon 2020 - EnPC INTRANS (Capacity Building on Energy Performance Contracting in European Markets in Transition). The analysis showed the particular favourability for three distinct types of EPC business models that proved to be successful in different socio-economic environments, facilitating energy efficiency investment from basic to intensive renovation initiatives.

The three identified models in question are essentially variations of the standard EPC model, which is also one of the models represented in this group.

3.1 Energy performance contracting light

3.1.1 Main model feature

EPC light is a zero-investment business approach: energy-saving measures with zero-investment costs are implemented by the ESCO, which includes an energy-saving guarantee within a contract duration of two to three years. The ESCO recommends further low or high investment measures to be paid by the building owner. It is up to the client to decide if the measures are to be implemented. If so, a share of the achieved savings of these measures can be attributed to the ESCO's savings guarantee. All technical devices still belong to the building owner.

3.1.2 Main Energy-Saving Measures

The most applied measures are the operational optimization of lighting systems, heating systems, ventilation systems, and the use of the warm water generation. Training sessions of the technical staff are included, and user motivation training can be provided. Mostly, the ESCO is responsible for the maintenance of the technical equipment.

3.1.3 Financing

The ESCO only has to calculate staff costs for the periodic inspection of the buildings including the technical devices. It receives bi-monthly or quarterly payments from a public entity and the remaining payment after the final invoice of the achieved energy savings.

3.1.4 Measurement and Verification

Energy savings are calculated based on energy invoices and a defined baseline of energy costs or (if not yet available) meter readings. An annual climate correction is taken into account, if necessary, and correction for changes in use or high-level savings by measures implemented by the building owner are applied.

3.1.5 Risks and de-risking strategies

The ESCO bears several risks concerning the energy cost baseline, the energy-saving guarantee, and operating errors. Additionally, the adjustments regarding user behaviour and other energy-saving measures made by the building owner can be risky as well as the controlling of the energy savings. Risk reduction strategies in this context are a sound saving calculation by the ESCO and experiences with the operation and optimization of technical equipment. In addition, the involvement of experienced project facilitators in the preparatory phase of the project is important as well as in the tendering procedure and evaluation of the savings. Furthermore, clear contract rules are necessary to avoid conflicts regarding adjustment mechanisms.

The bankruptcy of the ESCO is a possible risk for the public entity, but because all technical devices belong to the building owner, and there are no payments to a financial institution, this risk is very low. If savings are low performing, and the paid instalments are higher than the savings, there could a risk for the public entity as to whether the ESCO will pay back the difference between real achieved savings and paid instalments. To avoid these risks, the public entity has to involve an in-depth due-diligence process within tender evaluation process.

Main Advantages:

- Saving Guarantee and risk transfer to the ESCO (the risk level is low and always borne by the private partner),
- Detailed controlling of the annual energy consumption of every building,
- The real savings are measured and documented,
- No investment for technical measures,
- Profound proposals regarding low or high investment measures in the buildings,
- Cooperation between public entity and experienced ESCO,
- Entry for new ESCOs and PPP-unexperienced municipalities,
- Short contract duration.

3.2 Basic energy performance contracting

3.2.1 Main model feature

In common EPC basic-projects, the ESCO is accountable for the complete services: planning and installation of the technical measures, financing of the technical equipment, maintenance and energy management during the contract period. They guarantee the refunding of the complete costs through energy and maintenance costs savings during a fixed period. The public entity pays the cost savings that were actually achieved to the ESCO.

Fixed prices (payment) during the contract period (6–15 y.) related to the fulfilment of basic project requirements defined in procurement requirements mostly targeting maintenance measures. Sometimes the public entity receives a defined share of the savings; therefore, the municipality has to pay only the remaining share to the ESCO. Bonus-malus payments are also included if guaranteed energy and maintenance savings are over- or underachieved during the contract period. The technical equipment property is transferred from the ESCO to the municipality after the acceptance of the installation works by the municipality.

3.2.2 Main energy-saving measures

Depending on the detailed situation in the building and the economic calculation of the savings and costs, the following measures are possible in principle:

- Lighting, air conditioning, ventilation, pumps, control;
- Heating (heat pumps, biomass boiler, CHP, fossil fuel boiler), heating distribution, heat recovery systems, cooling systems, warm water generation, technical equipment for swimming pools, control;
- Showers, toilets;
- Thermal collector, solar cell, biomass boiler.

Sometimes, a few measures regarding fire protection, heritage protection, pollutant disposal and authorizations are included.

3.2.3 Financing

Financing by the ESCO is applied as a common financing model in EPC basic models. The ESCO frequently cooperates with a financial institution. The costs of the ESCO will be refunded by the energy cost savings and the maintenance cost savings. The public entity pays a monthly or quarterly instalment to the ESCO up to nearly 80% of the savings guarantee; the remaining amount is paid after the annual saving invoice.

Furthermore, there are few more options regarding financing of EPC basic projects:

An additional allowance by the public entity reduces the investment and financing costs of the ESCO. If many construction measures are included in the project, or the energy costs are very low and the refurbishment demand is high, the municipality has to finance a larger allowance.

Sometimes, the funding of the projects is supported by Energy Efficiency Funds to improve the access to available capital.

In few cases, public entities finance all planning and investment costs from their own communal budget or via interest subsidy loans for public entities. In this case, the municipalities pay back the annuity to the financial institution themselves.

Sometimes the municipality receives a share of the savings during the contract period; therefore, ESCOs can refund their costs only by the remaining amount of savings.

The financing conditions can be improved by the application of forfeiting. Thus, the ESCO receive a better interest rate, and the municipality confirms that annuities will be paid to the financial institution in every case.

3.2.4 Measurement and verification

Energy savings are validated with an energy price fixed during the contract period related to the measured and verified energy savings during the contract period. Energy savings are deducted from the energy and water bills or meter readings. Sometimes, fixed savings are defined, e.g. regarding saving through new lighting systems or pumps to avoid huge adjustments during the operation period. Because the ESCO has guaranteed the savings, it cares for the periodic controlling of the energy and water consumption, often supported by remote access to a building's energy management information system. All energy consumption-related data are collected and documented in the annual energy report and, together with adjustments, in the annual invoice of savings. Additionally, the ESCO is responsible for the quality assurance and maintenance of all installed technical devices.

3.2.5 Risks and de-risking strategies

Because of the greater extent of EPC basic measures and investments, the risks are higher comparable to the EPC light model. Risks exist related to the ESCO and related to the public entity. However, in every case, EPC basic includes a shifting of risks from the municipality to the ESCO. De-risking elements for both the ESCO and the public entity are integrated into the EPC basic business model.

3.2.6 Risks for ESCOs

ESCOs are commercial stakeholders, and they have to bear entrepreneurial risks. In the following, we describe the main significant risks and the most common de-risking strategies in current EPC basic-projects.

a) Economic risks:

- The level of annual energy savings. If the real savings are frequently below the guarantee and/or on a high level, then the ESCO cannot refund the complete costs by the savings.
- The right baseline: if the baseline is wrong, the energy-saving calculation is also incorrect.
- Planning errors lead to massive impairments of users or of the building.
- The level of investment is higher than calculated.
- Many energy-related measures of the principal within the contract period and/or the closure of buildings within the contract period.

These risks can be reduced by the integration of an experienced facilitator during project preparation (baseline check, plausibility check of saving guarantee and calculated costs, and planning check), detailed planning and calculation of savings and investments, possibly in cooperation with a professional engineer and a detailed measurement & verification system, including data from applied technical devices, error protocols, and other sources. Additionally, clear contract rules concerning baseline adaptation, climate and user-related adjustments, closure of buildings and energy-related measures of the public entity are necessary to minimize the risks for the ESCO.

b) Technical risks:

- Failure of the technical equipment or assembly mistakes,
- Operation risks, e.g. the technical staff of the principal adjust the technical set-points.

Again, clear contract rules regarding the responsibilities of the contract partners are crucial. The ESCO should have experiences with the used technical equipment considering the instructions from the manufacturers, and deploy qualified personnel or cooperate with professional partners.

c) Administrative risks:

- Delayed application for feed-in-tariff, subsidies or others by the municipality,
- Delayed acceptance of installation work.

All defined risks can be reduced by clear contract rules, especially the responsibilities should be exactly regulated.

3.2.7 Risks for public entities

Because the most important risks are shifted to the ESCO, the remaining risks for public entities are quite manageable:

- If the level of annual savings underachieves, the share of annuity for the financial institution, then the public entity cannot cover the instalment to the financial institution only through the savings. Thus, the municipality has to pay the difference from their own sources, mostly from the municipal budget;
- The bankruptcy of the ESCO.

Public entities can require an agreement fulfilment guarantee from the ESCO covered by an agreement between the ESCO and a financing institution for the implementation of the measures during the implementation period and after that. The municipality has the technical equipment property after the implementation period; therefore, the devices are operated by the technical staff of the municipality. This will also produce some savings, but definitely less than by the ESCO.

Main Advantages:

- Detailed controlling of the annual energy consumption of every building,
- The real savings are measured and documented,
- End energy savings of 20 to 50% (depending on the bundles of measures) and, therefore, reduced energy and water demand (heating, electricity),
- Higher market value of the building,
- Many measures are carried out in a relatively short time,
- Additional supplements to the calculated investment costs are not possible,
- The investment costs for the technical equipment are less in comparison to procurement without ESCO,
- Improved operational comfort (new control systems),
- The technical staff receive training and better qualifications,
- Comprehensive measurement bundles also including necessary non-energy-related measures.

3.3 Energy performance contracting plus

3.3.1 Main model feature

The EPC plus model is based on EPC basic. The mechanisms used are very similar: the energy-saving guarantee and the refunding of the complete costs through energy and maintenance costs savings during a fixed period; fixed prices (payment) during the contract period related to the fulfilment of basic project requirements; bonus-malus-payments regarding over- or under-achieved saving guarantee and the property transfer from the ESCO to the municipality.

However, the extent of measures is much broader: in addition to the installation of technical equipment, the ESCO is also accountable for the planning, installation and financing of the thermal insulation on the building envelope and of construction measures. Because of far higher investment costs and longer payback periods, this model is more sophisticated, particularly regarding financing.

3.3.2 Main Energy-Saving Measures

Depending on the detailed situation in the building and the calculation of the savings and costs, the following measures are possible in principle:

- Facade insulation; plinth insulation; basement ceiling insulation; roof ceiling insulation and replacement; replacement of windows, stairways, door replacement;
- Construction measures on walls, ceilings, floors, swimming pools;
- Lighting, air conditioning, ventilation, pumps, control;
- Heating (heat pumps, biomass boiler, CHP, fossil fuel boiler), heating distribution, heat recovery systems, cooling systems, warm water generation, technical equipment for swimming pools, control;

- Showers, toilets;
- Thermal collector, solar cell, biomass boiler.

3.3.3 Financing

Financing by the ESCO (in cooperation with a financing institution) or financing by the ESCO in combination with the capital of Energy Efficiency Funds are the most common financing models in existing EPC plus projects. The first model is based on comparable approach as EPC basic financing, but the contract duration ranges between 20-25 years.
In addition to these described options, there are other approaches:

- Sometimes the public authority gives an additional allowance reducing the higher investment costs. This allowance can be paid once after the implementation of the measures, or as instalment payments during the contract period.
- In addition, public subsidies can be involved in the project to decrease the investment costs.
- Additionally, a combination of further financing instruments is applied, e.g. internal financing, loans of financial institutions and funds' capital.
- Measurement and Verification: Construction and insulation measures do not have to be optimized during the contract period. Therefore, all energy savings (building and technical measures) are deducted from energy and water bills or meter readings validated with a fixed energy price.
- Furthermore, in EPC plus models, the ESCO is responsible for periodic controlling of energy consumption, the periodic adjustment of technical parameters, annual energy reports and annual invoices of savings.

3.3.4 Risks for ESCOs:

In addition to the risks described for the EPC basic model, there are few additional risks for EPC plus models:

a) Economic risks:

- The ESCOs have a technical background and often no experience with the calculation of thermal insulation measures. They have to cooperate with external architects, engineers or other companies and balance all complete savings.
- The calculation of savings through insulation measures depends on many user-related facts and should be carried out very thoroughly.
- Because the contract duration is much longer comparable to EPC basic, there are also more risks regarding the failure of the technical equipment and higher costs for the replacement of technical components.
- Because of the long contract times, the fixed interest period for the loan is also limited and ESCOs have to calculate with a possibly higher interest rate.

All these risks belong to the entrepreneurial risks and can be minimized by a cooperation with very experienced planners, by the deployment of proven calculation software and established products.

b) Technical and administrative risks:

- To consider changes in HVAC system for reduced heating and cooling loads is necessary. Poor planning based on few experience has to be avoided.
- Architectural quality is becoming more important in the context of measures on the building envelope. Therefore, heritage protection restrictions, higher costs and a higher need for coordination have to be taken into account.

In addition, experienced personnel for the planning should be deployed, and all eligible questions regarding measures on the building envelope should be harmonized before the dateline of the tendering procedure.

3.3.5 Main Advantages

- Reduced thermal and cooling loads in the buildings,
- Improved indoor climate quality (e.g. by new sun blinds),
- Better indoor space quality and, therefore, reduced illness of the users,
- Increased architectural quality via a modern façade,
- Wall insulation and highly efficient windows will reduce cold or hot indoor surfaces, which enables putting good quality working places much closer to the wall than before the retrofit,
- Better reputation of the building because of environmental friendly construction.

4 RENOVATION SCENARIOS

The revised energy efficiency directive (EED) stipulates the preparation of national strategic plans by member states that aim to reduce the energy consumption of the existing building stock by 80% compared to 2010.

According to a study published by Ecofys in June 2012 “Renovation Tracks for Europe up to 2050: Building renovation in Europe – what are the choices?”, building stock renovation is the most cost-effective way to reduce greenhouse-gas emissions, reduce energy dependency and simultaneously revitalize European economies. Specifically, three potential scenarios of future renovations were examined developed on the Ecofys Built Environment Analysis Model (BEAM), indicative of the renovation speed, the quantity (ambition) of energy efficiency improvement and use of renewable energy.

These three business models offer a transition from basic/shallow renovation attempts to widespread deep renovation initiatives as well as the best value in terms of created jobs, reduced emissions and improved living standards of the general population and should, therefore, represent the final goal of the international movements towards sustainable development. The three EPC models presented above are able to facilitate different levels of energy refurbishment according to these so-called renovation “tracks”, defined as follows.

4.1 Track 1: Shallow renovation

The first scenario features a fast renovation rate (3% a year) with a demand-side-driven retrofit standard (average level of refurbishment ambition, inclusive of market failures representative of potential measures that are not carried out because of anticipated obstructions such as high up-front investment, lack of information, cultural heritage and aesthetics, technical limitations, etc.). The scenario assumes low contributions from renewable energy sources with the majority of heating systems to be utilized operate on fossil fuels (gas and oil condensing boilers – 90%) while only 10% would use RES (air/water and ground/water heat pumps and biomass boilers). No solar thermal systems are included in this calculation. The track foresees that all existing building are to be retrofitted by 2045;no further retrofits are to be implemented for the last five years.

4.2 Track 2: Shallow renovation with renewable energy

This target scenario forecasts a slightly lower but still rapid renovation rate (2.3% per year) with a demand-side-driven retrofit standard similar to Track 1. The main difference is in the focus on the utilization of RES that forecasts high contribution from heating, ventilation and heat recovery systems. This assumes a more or less 100% rate for retrofits that utilize some form of RES (specified as 80% for air/water and ground/water heat pumps, 15% biomass boilers and five district heating systems with a growing share of RES). It also stipulates that 80% of all retrofits be equipped with solar thermal systems for domestic hot water and 100% have ventilation and heat recovery systems installed.

4.3 Track 3: Deep renovation

The deep renovation track is the most ambitious of all target scenarios. It features the same renovation rate as Track 2 (2.3% a year) and a demand-side-driven retrofit standard that is highly ambitious (representative of the level of passive housing) in terms of achieved energy savings. It is also projects a high level of utilized RES (70% for air/water and ground/water heat pumps, 15 % biomass boilers and 15 district heating systems with a growing share of RES) with all retrofits with ventilation and heat recovery systems in addition to 33% equipped with solar thermal systems for domestic hot water preparation.

It was concluded that the implementation of the deep renovation scenario (moderate yearly retrofit rate of 2.3% with high-energy efficiency ambition), would foster the largest energy consumption reduction, GHG savings and economic output (compared to shallow renovation with low and high use of renewable energy sources). While the cost of implementing all three scenarios were estimated to be roughly equal (from €8.2 to €8.8 trillion), the deep renovation was identified as offering the most promising outcome.

4.4 Results of the model projections

All three target scenarios assumed a maximum renovation rate of 3% taking into account average renovation cycles that last from 30 to 40 years. The renovation rates in Tracks 2 and 3, which are approximately 100% greater than the present rate, still ensure that the entire building stock would be renovated prior to 2050.

It was concluded that adopting the first target scenario (deep renovation) model could bring about a 80% reduction of energy required for space heating and hot water preparation, meet the CO_2 emission target (a 93% reduction) and perhaps even more importantly, create an additional 1.4 million jobs for highly educated and skilled workers until 2050 (almost twice as much compared to shallow renovation), building on the assumption that each million euros of investments creates one year of full employment for 17 workers.

Table 1: *Overview of target scenarios modelling results for the period 2012–2050. (Source: "Renovation Tracks for Europe up to 2050: Building renovation in Europe – what are the choices", Ecofys, June 2012)*

Scenario	Retrofit rate	C02-Emissions for space heating and domestic hot water EU27 by 2050 [Mt]	Final Energy use for space heating EU27 [TWh] by 2050 (without new buildings)	related reduction in final energy use by 2050 compared to 2010	Total Costs (investment costs **and** energy costs for space heating and domestic hot water, discounted costs for 2012–2050) [trillion euros]
Track 1	3.0%	498	1,987	32%	8.2
Track 2	2.3%	103	1,228	58%	8.8
Track 3	2.3%	93	613	80%	8.5

5 CONCLUSIONS

Although investment in energy efficiency is often shrugged off as not offering an attractive investment value in terms of risk-to-reward quotas, numerous real-life studies have refuted these false notions. Such was the case of the study carried out by the Jüllich Research Centre for the German KfW Development Bank, which showed that employing people on building refurbishment could result in immediate benefits for the greater economy. The study concluded that every euro invested in building refurbishment programmes returned a four- to five-fold capital return in terms of life-cycle impact. The reviewed investment created a total of 340,000 newly created local jobs. Additionally, according to the EU's energy efficiency review estimations, meeting a 40% energy efficiency target in 2030, mentioned in the European Commission consultation document, would stimulate annual economic growth of 4%, provide roughly a 3.15% increase of jobs and reduce fossil fuel imports by up to €505 billion every year, [6].

The first model that was recognized as effective was the EPC light business model, which is characterized by a low volume of investment and focuses on achieving energy savings exclusively through organizational measures, avoiding an intensive capital requirement in technical equipment and labour. The involved ESCO can guarantee savings in energy and thus maintenance costs in a similar fashion as in the EPC standard model, but with significantly less risk and capital requirement, making it a viable solution to underdeveloped markets in general, as well as SMEs that are interested in participating in the ESCO market, but lack the start-up capital, technical know-how and experience in the market.

The second one, as stated above, is the EPC basic/standard model that is also most commonly defined as a guaranteed savings contract between the ESCO and the client outlining different scenarios in terms of obligations, responsibilities as well as division of profits in the case of outperformance. The majority of risks are therefore taken over by the ESCO; nevertheless, the client can be severely exposed in the case of ESCO bankruptcy.

Finally, the conducted research of implemented ESCO projects also favoured the EPC Plus business model that is represented by the application of comprehensive refurbishment measures, including adaptation measures, which generally lowers the effective ROI and lengthens the effective payback period of the investment as a whole. This is, in general, a characteristic of deep renovation, for which it is not unusual for the payback period to exceed 20–25 years or even longer. Considering the deviations of energy price projections and the present volatility in the energy markets, it is unreasonable for investors to consider the outstanding risks associated with such a prolonged period in correlation with relatively small upside/reward potential. Therefore, the implementation of such business models is dependent on co-financing, either by building owners, public funds or less likely, private actors, which effectively channels risk and reduces the payback period, making it a viable opportunity when structured appropriately

The three EPC models outlined in the article are applicable to support the different target scenarios for building renovation and are quintessential tools to step-up the current actions and ambitions. The current level of activity in the field would roughly result in the fulfilment of the Track 1 target scenario, meaning we would severely underperform with regards to the energy saving, emission reduction and energy independence targets by 2050. Furthermore, even though deep renovation is currently viewed as economically unfeasible (or marginal), due to extensively long payback periods, we can conclude from the results that each target scenario requires about the same absolute amount of investment, from 8.2 to 8.8 billion euros. This points to the fact that there is a need to adapt financing and business mechanisms in the form of public-private partnership, which will maximize investment value and returns while outperforming the energy saving and emission reduction targets.

References

[1] **Jens. Laustsen; Paul. Ruyssevelt; Dan. Staniaszek; David. Strong:** *Europe's buildings under the microscope - A country-by-country review of the energy performance of buildings,* Buildings Performance Institute Europe (BPIE), 2011

[2] **Ministrstvo za infrastrukturo:** *Dolgoročna strategija za spodbujanje naložb energetske prenove stavb,* Portal Energetika, 2015

[3] **Konstanze. Stein:** *Description of identified EPC business models, provided within EnPC INTRANS EU project.*

[4] **Thomas. Boermans, Kjell. Bettgenhäuser, Markus. Offermann, Sven. Schimschar:** *Renovation Tracks for Europe up to 2050: Building renovation in Europe – what are the choices, Ecofys,* 2012

[5] **Forschungszentrum Jülich:** *Impact on public budgets of kfw promotional programmes in the field of energy-efficient building and rehabilitation,* KfW Bankengruppe, 2011

[6] **Arthur. Neslen:** *EU's energy efficiency review puts high target on agenda,* EurActiv website, 2014

[7] **Maria. van der Hoeven**: *Energy efficiency market report 2013 - Market Trends and Medium Term Prospects,* International Energy agency, 2013

Nomenclature

(Symbols)	(Symbol meaning)
t	time
EPC	Energy Performance Contracting
ESCO	Energy Service Company
EE	Energy efficiency
GHG	Greenhouse gases
BEAM	Built Environment Analysis Model
HVAC	Heating, Ventilation, and Air Conditioning
TWh	Terawatt hours
Mt	Megatons
CHP	Cogeneration of heat and power

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